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# LOW-TEMPERATURE THERMAL CONDUCTIVITY OF COMPOSITES:
## Alumina Fiber/Epoxy and Alumina Fiber/PEEK

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CONTENTS

## List of Tables

## List of Figures

Page

## List of Units and Symbols

### Definition of Symbols

$\lambda$ = thermal conductivity, W/(m•K)

$\Delta X$ = mean specimen thickness, m

A = mean specimen area, $m^2$

$\Delta T$ = steady-state temperature difference, K

### Unit Conversions

Temperature $T_C = T_K - 273.15$

$T_C = (T_F - 32)/1.8$

where $T_K$ is temperature in kelvins,

$T_C$ is temperature in degrees Celsius,

$T_F$ is temperature in degrees Fahrenheit,

Thermal Conductivity 1.000 W/(m•K) = 0.578 Btu/(hr•ft•°F)

= 6.94 Btu•in/(hr•$ft^2$•°F)

Pressure 1.000 Pa = 7.501 x $10^{-3}$ torr

Force 1.000 N = 0.22481 lb force

# Low-Temperature Thermal Conductivity of Composites:

## Alumina Fiber/Epoxy and Alumina Fiber/PEEK

The thermal conductivities of poly-ether-ether-ketone (PEEK), of alumina fiber in a matrix of PEEK, and of alumina fiber in a matrix of epoxy, were determined along with the effects of fiber orientation and thermal cycling. Thermal conductivity was measured over the temperature range 4.2 to 310 K using a steady-state apparatus.

These data are presented and discussed relative to specimen characteristics. It appears that after accounting for different fiber fractions in the specimens, the thermal conductivity of the PEEK composite material is less than that of the epoxy composite material in particular temperature ranges.

Key words: alumina; composite; epoxy; low temperature; PEEK; poly-ether-ether-ketone; thermal conductivity.

## Introduction

Polymer composites reinforced with alumina fibers have the potential of being excellent thermal-isolation materials for cryogenic applications. The higher elastic modulus of alumina compared to the traditional glass fiber will improve fatigue resistance. Utilization of the thermoplastic matrix material, poly-ether-ether-ketone (PEEK), also improves the fatigue performance compared to that of epoxy resins. PEEK, being a thermoplastic material, provides attractive advantages for production or fabrication and can be repaired more readily than thermoset materials.

Both thermal and mechanical behavior of composites to be used in cryogenic applications are important. The remainder of this paper deals with experimentally determined thermal conductivities; mechanical properties are being studied in a parallel NIST program.

## Apparatus

The system used to perform measurements of thermal conductivity is a modified version of a previously described "fixed-point" apparatus [1]. The specimen chamber is shown schematically in figure 1. It allows the thermal conductivity to be determined using fixed cold-side temperatures of 4 K (liquid helium), 76 K (liquid nitrogen), 194 K (mixture of dry ice and alcohol), and 273 K (mixture of ice and water). Measurements were performed by placing the chamber in one of the temperature-controlled baths and monitoring the power required to maintain a fixed temperature difference between the top and bottom blocks. The temperature differences between the hot and cold blocks were typically 1, 2, 4, 8, ..., 64 K.

Thermal conductivity measurements of a standard reference material, SRM 735, [2] indicated a total uncertainty of ± 5%. The $2\sigma$ uncertainty of the composite data being reported is less than ±5%, as evidenced by the deviation plots. Specimen-to-apparatus thermal contact resistance may cause the accuracy to be slightly worse for the composites than for the metallic SRM.

## Specimens

The materials studied were supplied by Ronald D. Kriz (Fracture & Deformation Division, National Institute of Standards & Technology). All of the alumina fibers contained in the epoxy and PEEK specimens are from a single source. While these fibers are actually composed of about 85 wt% $Al_2O_3$ and 15 wt% $SiO_2$ they will be referred to as alumina fibers. Neat PEEK is a specimen with no fiber reinforcement material. All specimens tested were prepared by two private companies. The specimens and nomenclature are identified in table 1.

**Table 1** Specimen Identification

| Specimen Identification | Comments | |
|---|---|---|
| EP-Al-0° | Epoxy/Alumina | heat flow parallel to fiber direction |
| EP-Al-90° | Epoxy/Alumina | heat flow perpendicular to fiber direction |
| PK-Al-1-0° | PEEK/Alumina | heat flow parallel to fiber direction |
| PK-Al-1-90° | PEEK/Alumina | heat flow perpendicular to fiber direction |
| PK-Al-2-0° | PEEK/Alumina | heat flow parallel to fiber direction |
| Neat-PK | Neat PEEK | absent of fibers |

The specimens were constructed by cementing smaller segments together with a thin layer of cyanoacrylate adhesive. The laminated specimens were ground to the shape of a uniform block with parallel (±0.003 cm) faces. The physical characteristics of the specimens are given in table 2. An estimate of the fiber content of the specimens is also given in table 2. These values were determined from photomicrographs of the specimen plane perpendicular to the fiber axes (Appendix A).

The steady-state measurements were made with a specimen in a vacuum environment of 1.07 x $10^{-2}$ Pa (8 x $10^{-5}$ torr). In each case the specimens had thermally conductive grease and indium foil (76 $\mu$m thick) on each contact surface to reduce thermal resistance. The load applied to the specimens, at room temperature, was a constant 4270 N (960 lb).

Table 2 Physical Characteristics of Specimens

| Specimen Identification | Area $cm^2$ | Thickness cm | Number of Segments | Alumina Fiber Volume Ratio % |
|---|---|---|---|---|
| EP-Al-0° | 0.5623 | 0.6359 | 2 | 59 |
| EP-Al-90° | 1.1909 | 0.3002 | 2 | |
| PK-Al-1-0° | 2.7327 | 0.8376 | 4 | 43 |
| PK-Al-1-90° | 3.0067 | 0.7239 | 2 | |
| PK-Al-2-0° | 1.4341 | 0.8310 | 4 | 52 |
| Neat-PK | 2.8159 | 0.6426 | 2 | |

## Results

The thermal conductivities of alumina fiber/epoxy and alumina fiber/PEEK were measured parallel (0°) and perpendicular (90°) to the fiber direction. A neat PEEK specimen was also measured. Data were taken over the temperature range 4.2 to 310 K. Since large temperature gradients are used and the thermal conductivity as a function of temperature is not simply linear, a thermal conductivity integral method [3] was used.

The function chosen to fit the thermal conductivity data is

$$\lambda(T) = \sum_{i=1}^{n} a_i \, [\ell n \, (T+1)]^i \qquad (1)$$

The experimental data, resulting values of $a_i$, and tabular data of the function for each of the six specimens, are presented in tables 4 through 21. To obtain proper fits it was necessary to weight some data. Plots of thermal conductivity and relative deviations, as a function of temperature, are given in figures 2 through 13. For

convenience, table 3 is an index of the plots and tables for all of the specimens tested.

**Table 3** Location Index for Figures and Tables of All Specimens.

| | Tables | | | Figures | |
|---|---|---|---|---|---|
| Specimen Identification | Table of Data | Table of Coeff's | Table of $\lambda(T)$ | Plot of $\lambda(T)$ | Plot of Deviations |
| EP-Al-0° | 4 | 5 | 6 | 2 | 3 |
| EP-Al-90° | 7 | 8 | 9 | 4 | 5 |
| PK-Al-1-0° | 10 | 11 | 12 | 6 | 7 |
| PK-Al-1-90° | 13 | 14 | 15 | 8 | 9 |
| PK-Al-2-0° | 16 | 17 | 18 | 10 | 11 |
| Neat-PK | 19 | 20 | 21 | 12 | 13 |

## Discussion

### Heat Flow Parallel to Fiber Direction

A direct comparison of the thermal conductivities of the PEEK/alumina composites with those of the epoxy/alumina composite cannot be made due to differences in the fiber content of the specimens tested (values listed in table 2). Because the alumina fiber material is a better thermal conductor than either matrix material, an increased fiber content should increase the thermal conductivity of a specimen. A simple parallel heat flow model was applied to the PEEK/alumina composites. It was found to be insufficient for predicting the thermal conductivity in other composites with different fiber volume ratios.

Figure 14 shows the thermal conductivity for the PK-Al-1-0° and PK-Al-2-0°. The curves for these two specimens are of similar shape with a vertical shift between them. The magnitude of this shift is ≃ 17 % and is uniform over the entire temperature range tested. It is likely that this shift can be attributed to the different fiber volume ratios of the specimens.

The thermal conductivity is related to the fiber volume ratio in the PEEK composite materials. Figures 15 and 16 shows this relationship for a family of temperatures using the data of PK-Al-1-0°, PK-Al-2-0° and Neat-PK. This relationship may be a good model for predicting results for other fiber volume ratios in the PEEK composite materials. A comparison of the thermal conductivity between the PEEK material and the epoxy material can be approximated. By utilizing the thermal conductivity-fiber volume ratio relationship, a PEEK-alumina fiber specimen with the same fiber volume ratio as the EP-Al-0° specimen can be determined. A linear extrapolation of the

fiber volume ratio, using the two PEEK-alumina specimens, was used to determine thermal conductivity as a function of temperature for a fiber volume ratio of 59%. Because the relationship between thermal conductivity and fiber volume ratios may not be a linear function, additional experimental data would be required to establish a more accurate relationship. The resulting calculated curve is compared with the EP-Al-0° data in figures 17 and 18. From this comparison, the thermal conductivity of a PEEK/alumina composite is slightly less than an epoxy/alumina composite of similar fiber volume ratio above ≃100 K and below ≃9 K. The thermal conductivity as a function of temperature between 9 and 100 K, for one matrix material, does not differ appreciably from that of the other material.

Heat Flow Perpendicular to Fiber Direction

The thermal conductivities of the specimens tested with the heat flow perpendicular to the alumina fibers are shown in figures 21 and 22. A crossover occurs at ≃23 K between the Neat-PK curve and the PK-Al-1-90° curve. Further study is required before an explanation of this effect can be suggested. The heat transfer characteristics may be further complicated by anisotropy in the PEEK material itself. The importance of this effect has yet to be determined.

Thermal Cycling of PEEK Composite

After initial tests were conducted on one of the original PEEK/alumina specimens (PK-Al-1-0°) it was thermally cycled. This experiment was done to determine if the conductivity of the PEEK composite material is affected by strains induced due to repeated thermal cycles. The specimen was cycled 25 times between room temperature and liquid nitrogen temperature (one of these cycles was to 4 K) and retested as before. Thermal conductivity was measured with the heat flow parallel to the fiber direction only. No effect on thermal conductivity due to this thermal cycling was detectable within the total experimental uncertainty (± 5%) outlined above.

The remaining figures are various comparisons giving additional perspectives. Logarithmic and linear presentations of the data are given to highlight the behavior of conductivity over ranges of both high and low temperatures.

## Acknowledgments

The authors wish to recognize B. J. Filla and J. G. Hust for their contributions in developing the apparatus and automating the control and acquisition features of this system. R. D. Kriz was primarily responsible for acquiring the specimens. Materials and fabrication were due to the efforts of I.C.I. Americas, Inc., Structural Composites Industries and Sumitomo Corporation.

## References

[1] Hust, J. G., Arvidson, J., "Thermal Conductivity of Glass Fiber/Epoxy Composite Support Bands for Cryogenic Dewars," Internal Report No. 275.03-78-2, National Bureau of Standards, Boulder, Colorado (1978).

[2] Hust, J. G., Sparks, L. L., "Thermal Conductivity of Austenitic Stainless Steel, SRM735, from 5 to 280 K," Nat. Bur. Stand. Special Publication 260-35 (1972).

[3] Hust, J. G., Lankford, A. B., "Comments on the measurement of Thermal Conductivity and Presentation of a Thermal Conductivity Integral Method," Int'l J. of Thermophysics 3, No. 1, 67-77 (1982).

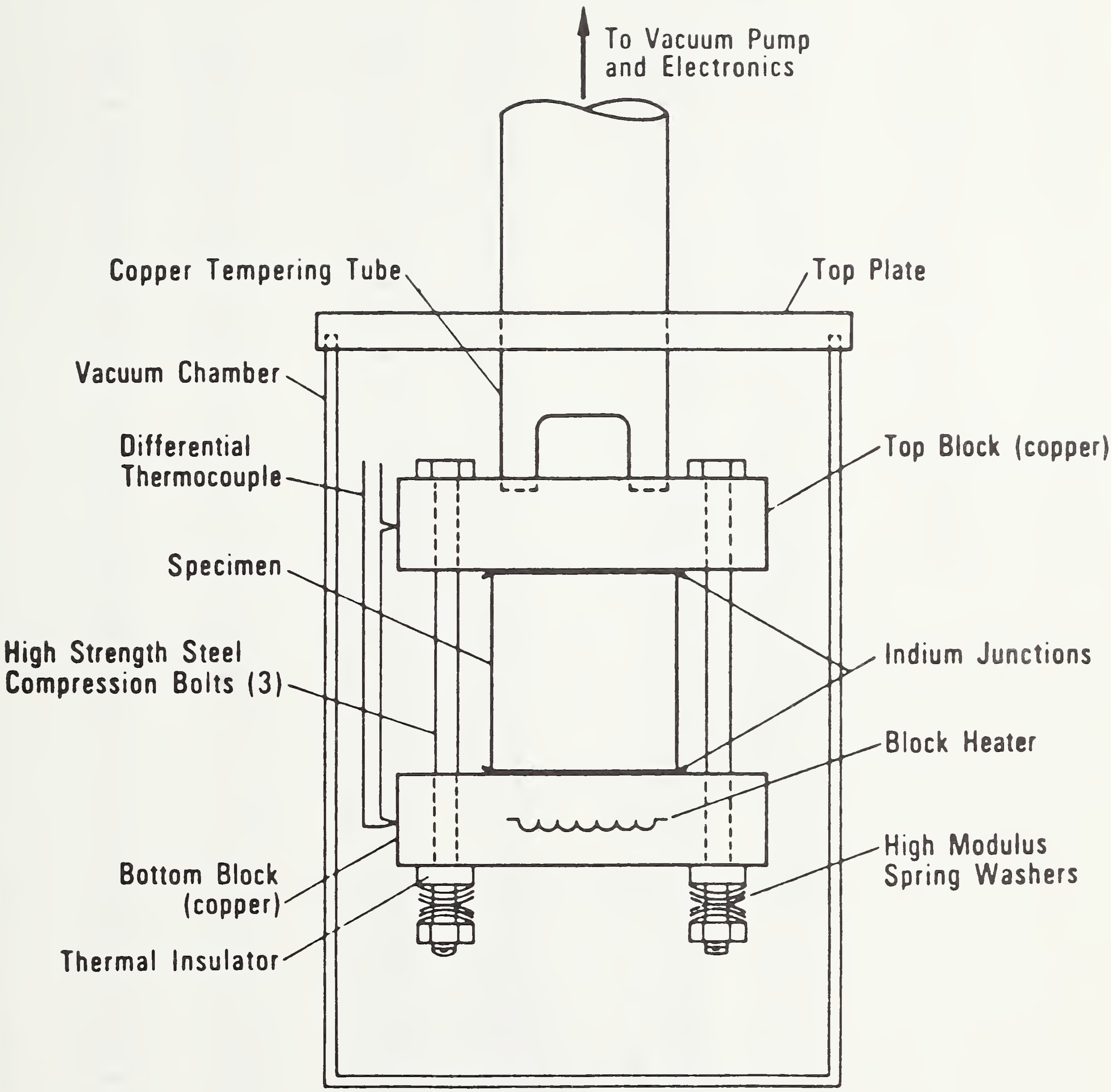



Figure 1   Specimen chamber for "fixed point" compression probe.

Table 4 Experimental Data for EP-Al-0°

| Average Temperature Kelvin | Thermal Conductivity W/(m·K) |
|---|---|
| 5.132 | 0.025 |
| 6.154 | 0.027 |
| 8.189 | 0.035 |
| 12.314 | 0.055 |
| 20.940 | 0.116 |
| 38.727 | 0.280 |
| 76.522 | 0.597 |
| 77.043 | 0.596 |
| 78.088 | 0.615 |
| 80.180 | 0.628 |
| 84.376 | 0.659 |
| 92.820 | 0.723 |
| 109.892 | 0.840 |
| 192.557 | 1.300 |
| 193.119 | 1.368 |
| 194.235 | 1.333 |
| 196.478 | 1.348 |
| 200.974 | 1.343 |
| 210.038 | 1.363 |
| 228.463 | 1.402 |
| 273.716 | 1.527 |
| 274.280 | 1.487 |
| 275.412 | 1.501 |
| 277.681 | 1.509 |
| 282.233 | 1.541 |
| 291.435 | 1.558 |
| 310.207 | 1.647 |

Table 5 Coefficients of $\lambda(T)$ for EP-Al-0°

| | |
|---|---|
| $a_1$ | 9.4838610E-02 |
| $a_2$ | -1.4612297E-01 |
| $a_3$ | 1.1101024E-01 |
| $a_4$ | -4.5386804E-02 |
| $a_5$ | 9.5660835E-03 |
| $a_6$ | -7.1230263E-04 |

Table 6 Thermal Conductivity Values as a Function of Temperature for Specimen EP-Al-0°

| T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) |
|---|---|---|---|---|---|---|---|
| 4.1000 | 0.0234 | 9.1000 | 0.0364 | 51.0000 | 0.3811 | 110.0000 | 0.8646 |
| 4.2000 | 0.0235 | 9.2000 | 0.0368 | 52.0000 | 0.3903 | 120.0000 | 0.9318 |
| 4.3000 | 0.0237 | 9.3000 | 0.0372 | 53.0000 | 0.3996 | 130.0000 | 0.9947 |
| 4.4000 | 0.0238 | 9.4000 | 0.0377 | 54.0000 | 0.4088 | 140.0000 | 1.0537 |
| 4.5000 | 0.0239 | 9.5000 | 0.0381 | 55.0000 | 0.4180 | 150.0000 | 1.1088 |
| 4.6000 | 0.0241 | 9.6000 | 0.0385 | 56.0000 | 0.4272 | 160.0000 | 1.1602 |
| 4.7000 | 0.0242 | 9.7000 | 0.0389 | 57.0000 | 0.4363 | 170.0000 | 1.2081 |
| 4.8000 | 0.0244 | 9.8000 | 0.0393 | 58.0000 | 0.4454 | 180.0000 | 1.2526 |
| 4.9000 | 0.0245 | 9.9000 | 0.0398 | 59.0000 | 0.4545 | 190.0000 | 1.2940 |
| 5.0000 | 0.0247 | 10.0000 | 0.0402 | 60.0000 | 0.4636 | 200.0000 | 1.3322 |
| 5.1000 | 0.0248 | 11.0000 | 0.0448 | 61.0000 | 0.4726 | 210.0000 | 1.3675 |
| 5.2000 | 0.0250 | 12.0000 | 0.0499 | 62.0000 | 0.4816 | 220.0000 | 1.4000 |
| 5.3000 | 0.0252 | 13.0000 | 0.0554 | 63.0000 | 0.4905 | 230.0000 | 1.4298 |
| 5.4000 | 0.0254 | 14.0000 | 0.0612 | 64.0000 | 0.4995 | 240.0000 | 1.4571 |
| 5.5000 | 0.0256 | 15.0000 | 0.0674 | 65.0000 | 0.5084 | 250.0000 | 1.4820 |
| 5.6000 | 0.0258 | 16.0000 | 0.0739 | 66.0000 | 0.5172 | 260.0000 | 1.5044 |
| 5.7000 | 0.0260 | 17.0000 | 0.0807 | 67.0000 | 0.5260 | 270.0000 | 1.5247 |
| 5.8000 | 0.0262 | 18.0000 | 0.0877 | 68.0000 | 0.5348 | 280.0000 | 1.5428 |
| 5.9000 | 0.0264 | 19.0000 | 0.0950 | 69.0000 | 0.5435 | 290.0000 | 1.5588 |
| 6.0000 | 0.0267 | 20.0000 | 0.1025 | 70.0000 | 0.5522 | 300.0000 | 1.5728 |
| 6.1000 | 0.0269 | 21.0000 | 0.1103 | 71.0000 | 0.5609 | 310.0000 | 1.5849 |
| 6.2000 | 0.0271 | 22.0000 | 0.1182 | 72.0000 | 0.5695 | 320.0000 | 1.5952 |
| 6.3000 | 0.0274 | 23.0000 | 0.1263 | 73.0000 | 0.5780 | 330.0000 | 1.6037 |
| 6.4000 | 0.0276 | 24.0000 | 0.1345 | 74.0000 | 0.5866 | 340.0000 | 1.6105 |
| 6.5000 | 0.0279 | 25.0000 | 0.1429 | 75.0000 | 0.5951 | | |
| 6.6000 | 0.0281 | 26.0000 | 0.1514 | 76.0000 | 0.6035 | | |
| 6.7000 | 0.0284 | 27.0000 | 0.1600 | 77.0000 | 0.6119 | | |
| 6.8000 | 0.0287 | 28.0000 | 0.1687 | 78.0000 | 0.6203 | | |
| 6.9000 | 0.0290 | 29.0000 | 0.1776 | 79.0000 | 0.6286 | | |
| 7.0000 | 0.0293 | 30.0000 | 0.1865 | 80.0000 | 0.6369 | | |
| 7.1000 | 0.0295 | 31.0000 | 0.1954 | 81.0000 | 0.6451 | | |
| 7.2000 | 0.0298 | 32.0000 | 0.2045 | 82.0000 | 0.6533 | | |
| 7.3000 | 0.0301 | 33.0000 | 0.2136 | 83.0000 | 0.6614 | | |
| 7.4000 | 0.0304 | 34.0000 | 0.2227 | 84.0000 | 0.6695 | | |
| 7.5000 | 0.0308 | 35.0000 | 0.2319 | 85.0000 | 0.6776 | | |
| 7.6000 | 0.0311 | 36.0000 | 0.2411 | 86.0000 | 0.6856 | | |
| 7.7000 | 0.0314 | 37.0000 | 0.2504 | 87.0000 | 0.6935 | | |
| 7.8000 | 0.0317 | 38.0000 | 0.2597 | 88.0000 | 0.7015 | | |
| 7.9000 | 0.0321 | 39.0000 | 0.2690 | 89.0000 | 0.7094 | | |
| 8.0000 | 0.0324 | 40.0000 | 0.2783 | 90.0000 | 0.7172 | | |
| 8.1000 | 0.0327 | 41.0000 | 0.2877 | 91.0000 | 0.7250 | | |
| 8.2000 | 0.0331 | 42.0000 | 0.2970 | 92.0000 | 0.7327 | | |
| 8.3000 | 0.0334 | 43.0000 | 0.3064 | 93.0000 | 0.7404 | | |
| 8.4000 | 0.0338 | 44.0000 | 0.3158 | 94.0000 | 0.7481 | | |
| 8.5000 | 0.0342 | 45.0000 | 0.3251 | 95.0000 | 0.7557 | | |
| 8.6000 | 0.0345 | 46.0000 | 0.3345 | 96.0000 | 0.7633 | | |
| 8.7000 | 0.0349 | 47.0000 | 0.3438 | 97.0000 | 0.7708 | | |
| 8.8000 | 0.0353 | 48.0000 | 0.3531 | 98.0000 | 0.7783 | | |
| 8.9000 | 0.0357 | 49.0000 | 0.3625 | 99.0000 | 0.7857 | | |
| 9.0000 | 0.0361 | 50.0000 | 0.3718 | 100.0000 | 0.7931 | | |

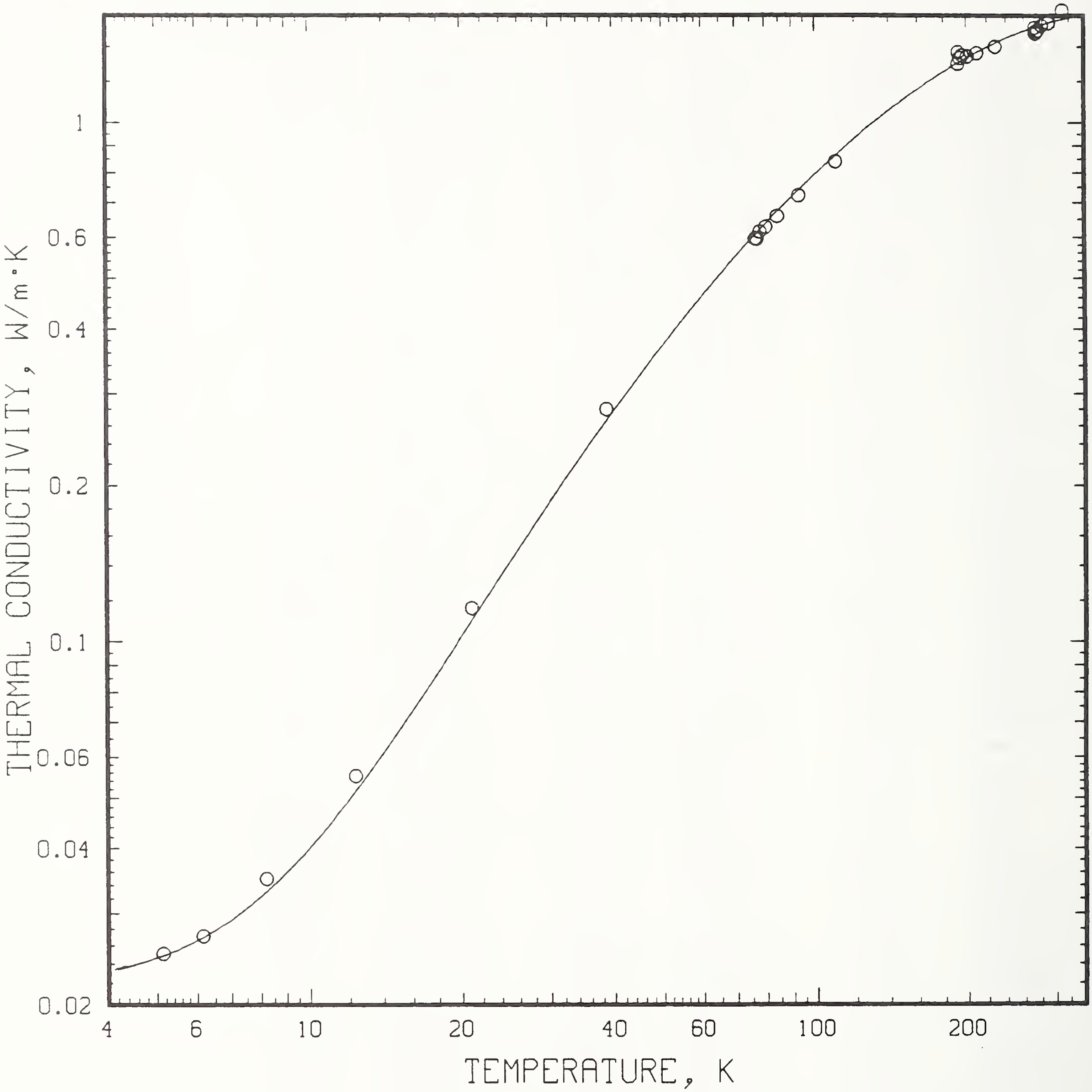



Figure 2 Thermal conductivity of specimen EP-Al-0°. Experimental data are presented as discrete points.

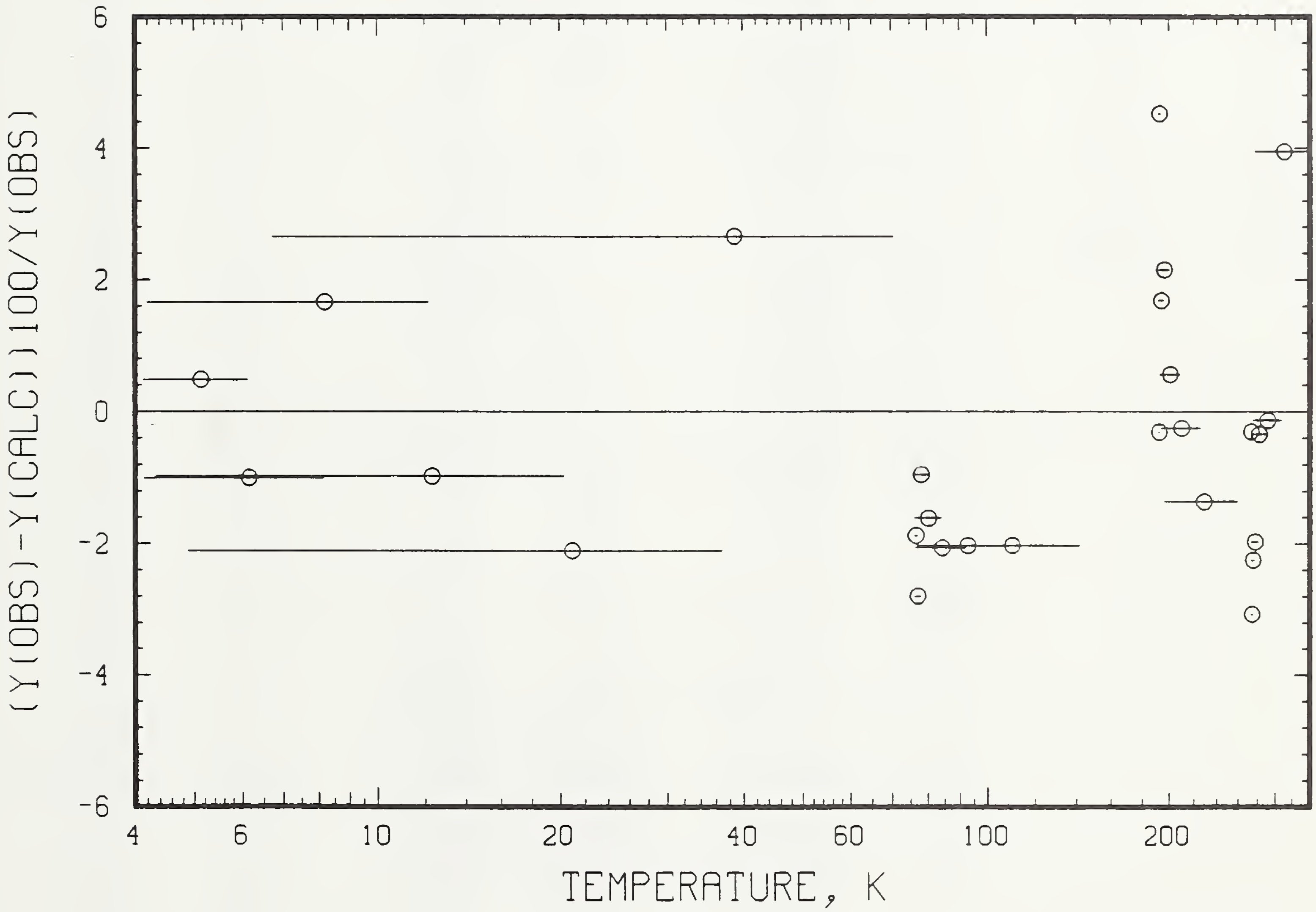



**Figure 3** Relative deviations of the experimental and calculated thermal conductivity integrals for specimen EP-Al-0°. (The horizontal bar indicates the span of temperature for each run).

Table 7 Experimental Data for EP-Al-90°

| Average Temperature Kelvin | Thermal Conductivity W/(m·K) |
|---|---|
| 4.630 | 0.014 |
| 5.140 | 0.016 |
| 6.169 | 0.019 |
| 8.273 | 0.027 |
| 12.610 | 0.047 |
| 21.908 | 0.103 |
| 41.595 | 0.231 |
| 76.552 | 0.427 |
| 77.103 | 0.427 |
| 78.208 | 0.434 |
| 80.427 | 0.444 |
| 84.890 | 0.465 |
| 93.923 | 0.499 |
| 112.346 | 0.563 |
| 192.620 | 0.801 |
| 193.241 | 0.806 |
| 194.484 | 0.808 |
| 196.977 | 0.811 |
| 201.987 | 0.819 |
| 212.081 | 0.827 |
| 278.117 | 0.926 |
| 283.123 | 0.937 |
| 293.259 | 0.961 |
| 306.262 | 0.962 |

Table 8 Coefficients of $\lambda(T)$ for EP-Al-90°

| | |
|---|---|
| $a_1$ | -4.7747384E-02 |
| $a_2$ | 9.8421893E-02 |
| $a_3$ | -6.4348531E-02 |
| $a_4$ | 1.7615317E-02 |
| $a_5$ | -1.4383095E-03 |

Table 9 Thermal Conductivity Values as a Function of Temperature for Specimen EP-Al-90°

| T Kelvin | $\lambda(T)$ W/(m·K) | T Kelvin | $\lambda(T)$ W/(m·K) | T Kelvin | $\lambda(T)$ W/(m·K) | T Kelvin | $\lambda(T)$ W/(m·K) |
|---|---|---|---|---|---|---|---|
| 4.1000 | 0.0128 | 9.1000 | 0.0288 | 51.0000 | 0.2868 | 110.0000 | 0.5699 |
| 4.2000 | 0.0131 | 9.2000 | 0.0292 | 52.0000 | 0.2927 | 120.0000 | 0.6063 |
| 4.3000 | 0.0133 | 9.3000 | 0.0296 | 53.0000 | 0.2986 | 130.0000 | 0.6401 |
| 4.4000 | 0.0136 | 9.4000 | 0.0300 | 54.0000 | 0.3045 | 140.0000 | 0.6714 |
| 4.5000 | 0.0139 | 9.5000 | 0.0304 | 55.0000 | 0.3103 | 150.0000 | 0.7004 |
| 4.6000 | 0.0142 | 9.6000 | 0.0309 | 56.0000 | 0.3161 | 160.0000 | 0.7274 |
| 4.7000 | 0.0144 | 9.7000 | 0.0313 | 57.0000 | 0.3218 | 170.0000 | 0.7524 |
| 4.8000 | 0.0147 | 9.8000 | 0.0317 | 58.0000 | 0.3275 | 180.0000 | 0.7756 |
| 4.9000 | 0.0150 | 9.9000 | 0.0321 | 59.0000 | 0.3331 | 190.0000 | 0.7972 |
| 5.0000 | 0.0153 | 10.0000 | 0.0326 | 60.0000 | 0.3387 | 200.0000 | 0.8173 |
| 5.1000 | 0.0155 | 11.0000 | 0.0371 | 61.0000 | 0.3443 | 210.0000 | 0.8359 |
| 5.2000 | 0.0158 | 12.0000 | 0.0419 | 62.0000 | 0.3498 | 220.0000 | 0.8531 |
| 5.3000 | 0.0161 | 13.0000 | 0.0471 | 63.0000 | 0.3553 | 230.0000 | 0.8691 |
| 5.4000 | 0.0164 | 14.0000 | 0.0524 | 64.0000 | 0.3607 | 240.0000 | 0.8838 |
| 5.5000 | 0.0166 | 15.0000 | 0.0580 | 65.0000 | 0.3661 | 250.0000 | 0.8975 |
| 5.6000 | 0.0169 | 16.0000 | 0.0638 | 66.0000 | 0.3714 | 260.0000 | 0.9101 |
| 5.7000 | 0.0172 | 17.0000 | 0.0697 | 67.0000 | 0.3768 | 270.0000 | 0.9217 |
| 5.8000 | 0.0175 | 18.0000 | 0.0758 | 68.0000 | 0.3820 | 280.0000 | 0.9323 |
| 5.9000 | 0.0178 | 19.0000 | 0.0819 | 69.0000 | 0.3873 | 290.0000 | 0.9421 |
| 6.0000 | 0.0181 | 20.0000 | 0.0882 | 70.0000 | 0.3924 | 300.0000 | 0.9510 |
| 6.1000 | 0.0184 | 21.0000 | 0.0946 | 71.0000 | 0.3976 | 310.0000 | 0.9592 |
| 6.2000 | 0.0187 | 22.0000 | 0.1010 | 72.0000 | 0.4027 | 320.0000 | 0.9665 |
| 6.3000 | 0.0190 | 23.0000 | 0.1075 | 73.0000 | 0.4078 | 330.0000 | 0.9732 |
| 6.4000 | 0.0193 | 24.0000 | 0.1140 | 74.0000 | 0.4128 | | |
| 6.5000 | 0.0196 | 25.0000 | 0.1206 | 75.0000 | 0.4178 | | |
| 6.6000 | 0.0199 | 26.0000 | 0.1272 | 76.0000 | 0.4227 | | |
| 6.7000 | 0.0202 | 27.0000 | 0.1338 | 77.0000 | 0.4276 | | |
| 6.8000 | 0.0205 | 28.0000 | 0.1404 | 78.0000 | 0.4325 | | |
| 6.9000 | 0.0208 | 29.0000 | 0.1470 | 79.0000 | 0.4373 | | |
| 7.0000 | 0.0211 | 30.0000 | 0.1536 | 80.0000 | 0.4421 | | |
| 7.1000 | 0.0215 | 31.0000 | 0.1602 | 81.0000 | 0.4469 | | |
| 7.2000 | 0.0218 | 32.0000 | 0.1668 | 82.0000 | 0.4516 | | |
| 7.3000 | 0.0221 | 33.0000 | 0.1734 | 83.0000 | 0.4563 | | |
| 7.4000 | 0.0225 | 34.0000 | 0.1800 | 84.0000 | 0.4609 | | |
| 7.5000 | 0.0228 | 35.0000 | 0.1865 | 85.0000 | 0.4656 | | |
| 7.6000 | 0.0232 | 36.0000 | 0.1930 | 86.0000 | 0.4701 | | |
| 7.7000 | 0.0235 | 37.0000 | 0.1995 | 87.0000 | 0.4747 | | |
| 7.8000 | 0.0239 | 38.0000 | 0.2060 | 88.0000 | 0.4792 | | |
| 7.9000 | 0.0242 | 39.0000 | 0.2124 | 89.0000 | 0.4836 | | |
| 8.0000 | 0.0246 | 40.0000 | 0.2188 | 90.0000 | 0.4881 | | |
| 8.1000 | 0.0249 | 41.0000 | 0.2252 | 91.0000 | 0.4925 | | |
| 8.2000 | 0.0253 | 42.0000 | 0.2315 | 92.0000 | 0.4968 | | |
| 8.3000 | 0.0257 | 43.0000 | 0.2378 | 93.0000 | 0.5012 | | |
| 8.4000 | 0.0260 | 44.0000 | 0.2441 | 94.0000 | 0.5055 | | |
| 8.5000 | 0.0264 | 45.0000 | 0.2503 | 95.0000 | 0.5097 | | |
| 8.6000 | 0.0268 | 46.0000 | 0.2565 | 96.0000 | 0.5140 | | |
| 8.7000 | 0.0272 | 47.0000 | 0.2626 | 97.0000 | 0.5182 | | |
| 8.8000 | 0.0276 | 48.0000 | 0.2687 | 98.0000 | 0.5223 | | |
| 8.9000 | 0.0280 | 49.0000 | 0.2748 | 99.0000 | 0.5265 | | |
| 9.0000 | 0.0284 | 50.0000 | 0.2808 | 100.0000 | 0.5306 | | |

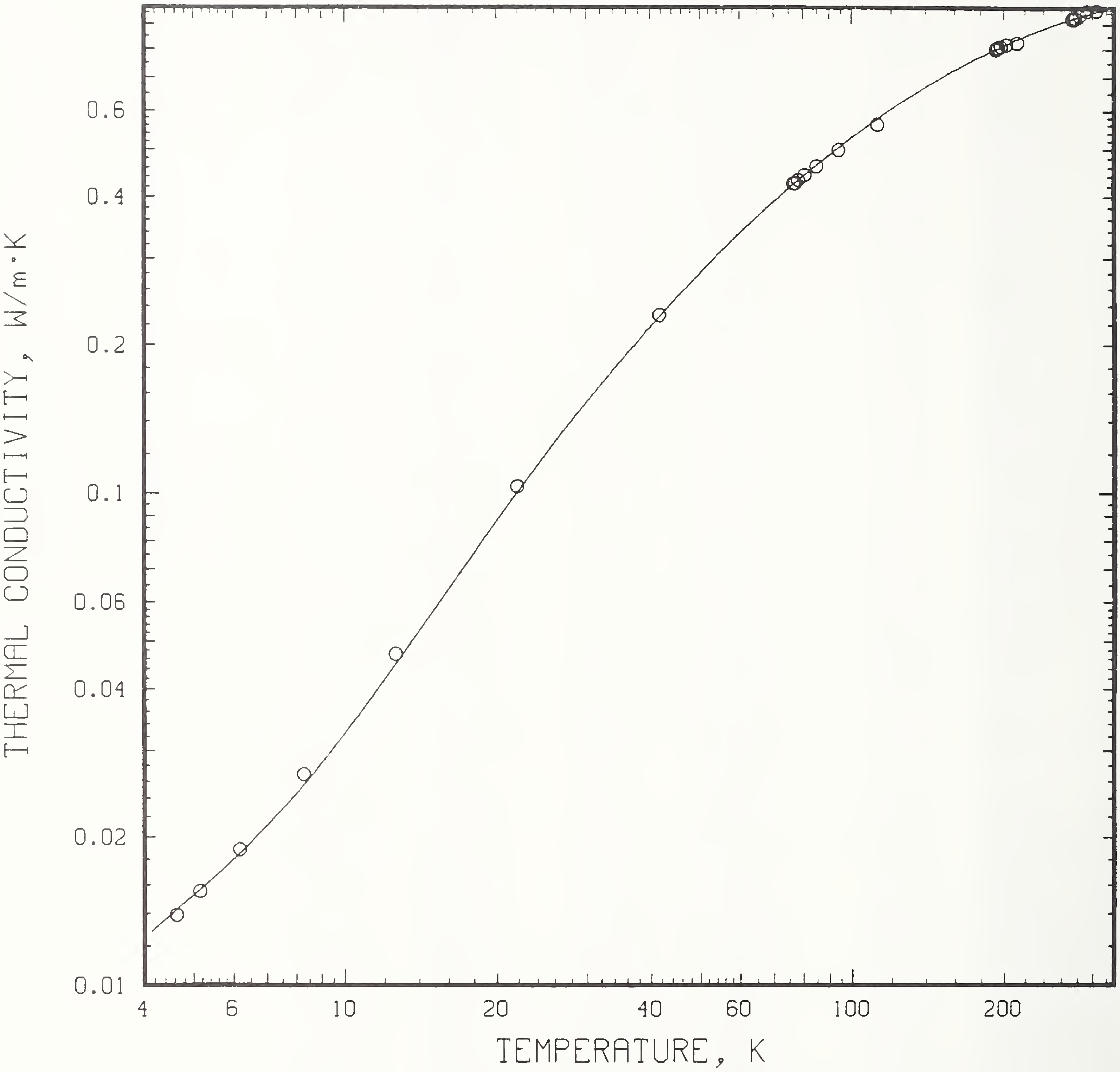



**Figure 4** Thermal conductivity of specimen EP-Al-90°. Experimental data are presented as discrete points.

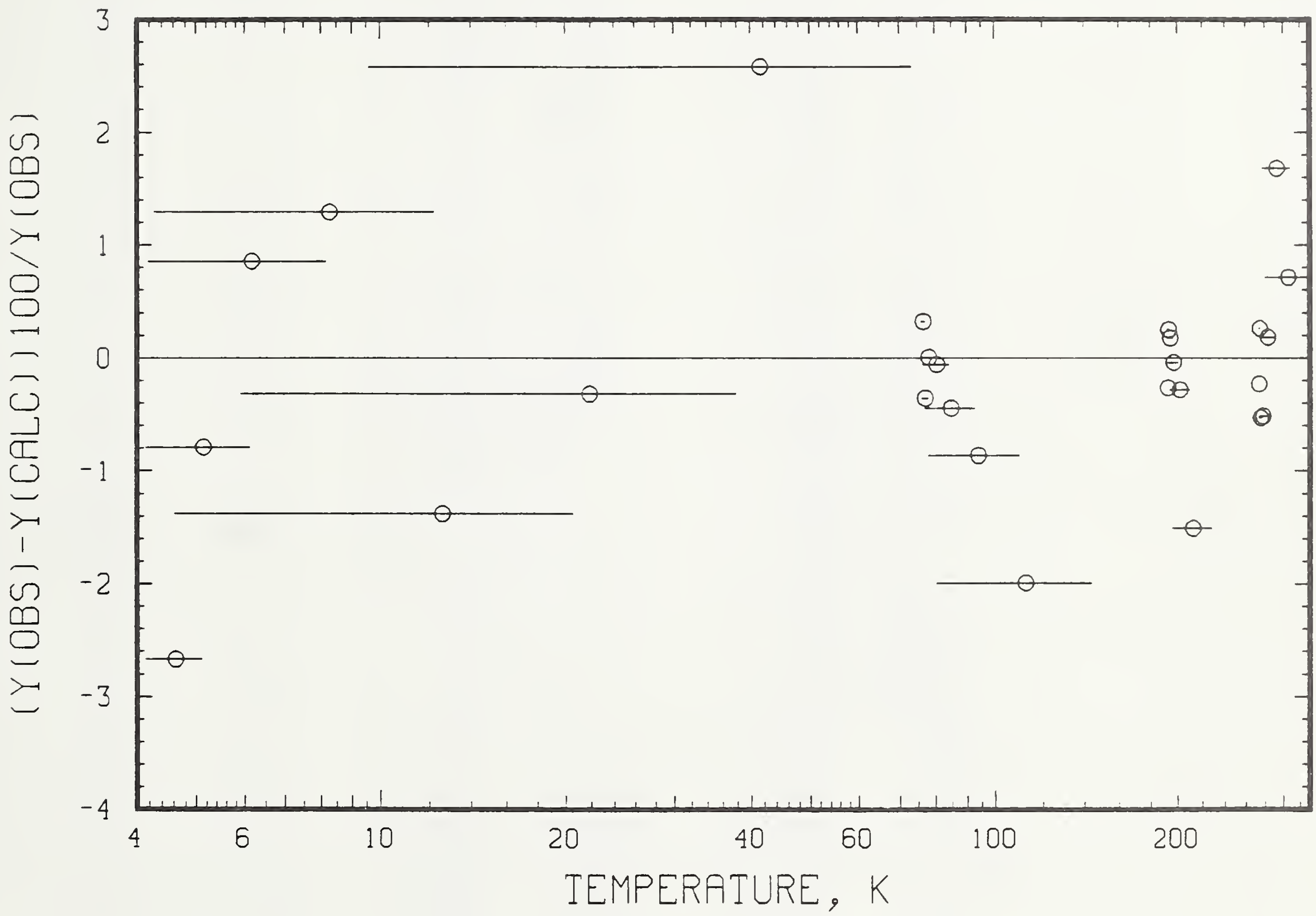



**Figure 5** Relative deviations of the experimental and calculated thermal conductivity integrals for specimen EP-Al-90°.

Table 10 Experimental Data for PK-Al-1-0°

| Average Temperature Kelvin | Thermal Conductivity W/(m·K) |
|---|---|
| 4.628 | 0.013 |
| 5.138 | 0.014 |
| 6.160 | 0.017 |
| 8.250 | 0.024 |
| 12.508 | 0.041 |
| 21.525 | 0.088 |
| 40.611 | 0.203 |
| 40.625 | 0.205 |
| 76.542 | 0.406 |
| 77.085 | 0.411 |
| 78.173 | 0.419 |
| 80.354 | 0.431 |
| 84.743 | 0.455 |
| 93.635 | 0.501 |
| 111.841 | 0.590 |
| 192.617 | 0.944 |
| 193.233 | 0.937 |
| 194.467 | 0.939 |
| 196.941 | 0.942 |
| 201.921 | 0.955 |
| 211.988 | 0.975 |
| 232.568 | 1.015 |
| 273.769 | 1.119 |
| 274.390 | 1.126 |
| 275.630 | 1.124 |
| 278.119 | 1.129 |
| 283.131 | 1.146 |
| 293.267 | 1.173 |
| 305.906 | 1.196 |

**Table 11** Coefficients of $\lambda(T)$ for PK-Al-1-0°

| | |
|---|---|
| $a_1$ | 1.2517495E-01 |
| $a_2$ | -2.1465594E-01 |
| $a_3$ | 1.5127037E-01 |
| $a_4$ | -5.2639361E-02 |
| $a_5$ | 9.2557441E-03 |
| $a_6$ | -6.0375954E-04 |

Table 12 Thermal Conductivity Values as a Function of Temperature for Specimen PK-Al-1-0°

| T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) |
|---|---|---|---|---|---|---|---|
| 4.1000 | 0.0124 | 9.1000 | 0.0267 | 51.0000 | 0.2609 | 110.0000 | 0.5903 |
| 4.2000 | 0.0125 | 9.2000 | 0.0270 | 52.0000 | 0.2670 | 120.0000 | 0.6386 |
| 4.3000 | 0.0126 | 9.3000 | 0.0274 | 53.0000 | 0.2731 | 130.0000 | 0.6845 |
| 4.4000 | 0.0127 | 9.4000 | 0.0278 | 54.0000 | 0.2792 | 140.0000 | 0.7282 |
| 4.5000 | 0.0129 | 9.5000 | 0.0282 | 55.0000 | 0.2852 | 150.0000 | 0.7697 |
| 4.6000 | 0.0130 | 9.6000 | 0.0286 | 56.0000 | 0.2913 | 160.0000 | 0.8090 |
| 4.7000 | 0.0132 | 9.7000 | 0.0290 | 57.0000 | 0.2973 | 170.0000 | 0.8463 |
| 4.8000 | 0.0133 | 9.8000 | 0.0294 | 58.0000 | 0.3033 | 180.0000 | 0.8816 |
| 4.9000 | 0.0135 | 9.9000 | 0.0298 | 59.0000 | 0.3093 | 190.0000 | 0.9151 |
| 5.0000 | 0.0137 | 10.0000 | 0.0302 | 60.0000 | 0.3153 | 200.0000 | 0.9466 |
| 5.1000 | 0.0139 | 11.0000 | 0.0344 | 61.0000 | 0.3213 | 210.0000 | 0.9764 |
| 5.2000 | 0.0141 | 12.0000 | 0.0388 | 62.0000 | 0.3273 | 220.0000 | 1.0045 |
| 5.3000 | 0.0143 | 13.0000 | 0.0432 | 63.0000 | 0.3332 | 230.0000 | 1.0310 |
| 5.4000 | 0.0146 | 14.0000 | 0.0479 | 64.0000 | 0.3392 | 240.0000 | 1.0559 |
| 5.5000 | 0.0148 | 15.0000 | 0.0526 | 65.0000 | 0.3451 | 250.0000 | 1.0792 |
| 5.6000 | 0.0150 | 16.0000 | 0.0575 | 66.0000 | 0.3510 | 260.0000 | 1.1011 |
| 5.7000 | 0.0153 | 17.0000 | 0.0625 | 67.0000 | 0.3569 | 270.0000 | 1.1216 |
| 5.8000 | 0.0156 | 18.0000 | 0.0675 | 68.0000 | 0.3628 | 280.0000 | 1.1408 |
| 5.9000 | 0.0158 | 19.0000 | 0.0727 | 69.0000 | 0.3686 | 290.0000 | 1.1586 |
| 6.0000 | 0.0161 | 20.0000 | 0.0779 | 70.0000 | 0.3744 | 300.0000 | 1.1751 |
| 6.1000 | 0.0164 | 21.0000 | 0.0833 | 71.0000 | 0.3803 | 310.0000 | 1.1904 |
| 6.2000 | 0.0167 | 22.0000 | 0.0887 | 72.0000 | 0.3861 | 320.0000 | 1.2046 |
| 6.3000 | 0.0169 | 23.0000 | 0.0942 | 73.0000 | 0.3918 | 330.0000 | 1.2176 |
| 6.4000 | 0.0172 | 24.0000 | 0.0997 | 74.0000 | 0.3976 | | |
| 6.5000 | 0.0175 | 25.0000 | 0.1053 | 75.0000 | 0.4033 | | |
| 6.6000 | 0.0178 | 26.0000 | 0.1110 | 76.0000 | 0.4091 | | |
| 6.7000 | 0.0181 | 27.0000 | 0.1167 | 77.0000 | 0.4148 | | |
| 6.8000 | 0.0185 | 28.0000 | 0.1224 | 78.0000 | 0.4204 | | |
| 6.9000 | 0.0188 | 29.0000 | 0.1282 | 79.0000 | 0.4261 | | |
| 7.0000 | 0.0191 | 30.0000 | 0.1341 | 80.0000 | 0.4317 | | |
| 7.1000 | 0.0194 | 31.0000 | 0.1399 | 81.0000 | 0.4373 | | |
| 7.2000 | 0.0198 | 32.0000 | 0.1458 | 82.0000 | 0.4429 | | |
| 7.3000 | 0.0201 | 33.0000 | 0.1518 | 83.0000 | 0.4485 | | |
| 7.4000 | 0.0204 | 34.0000 | 0.1577 | 84.0000 | 0.4541 | | |
| 7.5000 | 0.0208 | 35.0000 | 0.1637 | 85.0000 | 0.4596 | | |
| 7.6000 | 0.0211 | 36.0000 | 0.1697 | 86.0000 | 0.4651 | | |
| 7.7000 | 0.0215 | 37.0000 | 0.1757 | 87.0000 | 0.4706 | | |
| 7.8000 | 0.0218 | 38.0000 | 0.1818 | 88.0000 | 0.4760 | | |
| 7.9000 | 0.0222 | 39.0000 | 0.1878 | 89.0000 | 0.4815 | | |
| 8.0000 | 0.0225 | 40.0000 | 0.1939 | 90.0000 | 0.4869 | | |
| 8.1000 | 0.0229 | 41.0000 | 0.2000 | 91.0000 | 0.4923 | | |
| 8.2000 | 0.0233 | 42.0000 | 0.2061 | 92.0000 | 0.4976 | | |
| 8.3000 | 0.0236 | 43.0000 | 0.2122 | 93.0000 | 0.5030 | | |
| 8.4000 | 0.0240 | 44.0000 | 0.2183 | 94.0000 | 0.5083 | | |
| 8.5000 | 0.0244 | 45.0000 | 0.2244 | 95.0000 | 0.5136 | | |
| 8.6000 | 0.0247 | 46.0000 | 0.2305 | 96.0000 | 0.5189 | | |
| 8.7000 | 0.0251 | 47.0000 | 0.2366 | 97.0000 | 0.5241 | | |
| 8.8000 | 0.0255 | 48.0000 | 0.2427 | 98.0000 | 0.5294 | | |
| 8.9000 | 0.0259 | 49.0000 | 0.2488 | 99.0000 | 0.5346 | | |
| 9.0000 | 0.0263 | 50.0000 | 0.2548 | 100.0000 | 0.5398 | | |

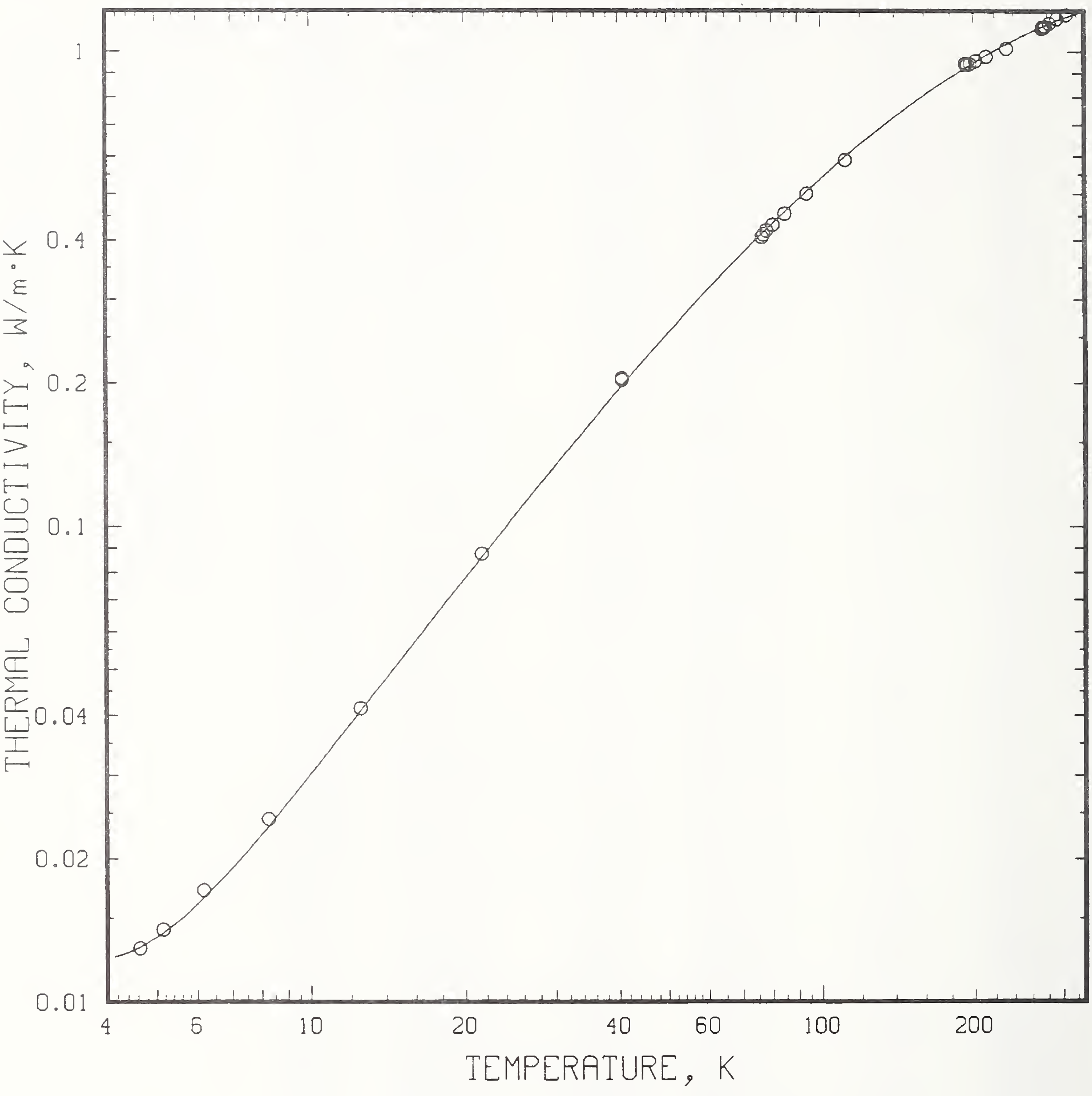



Figure 6 Thermal conductivity of specimen PK-Al-1-0°. Experimental data are presented as discrete points.

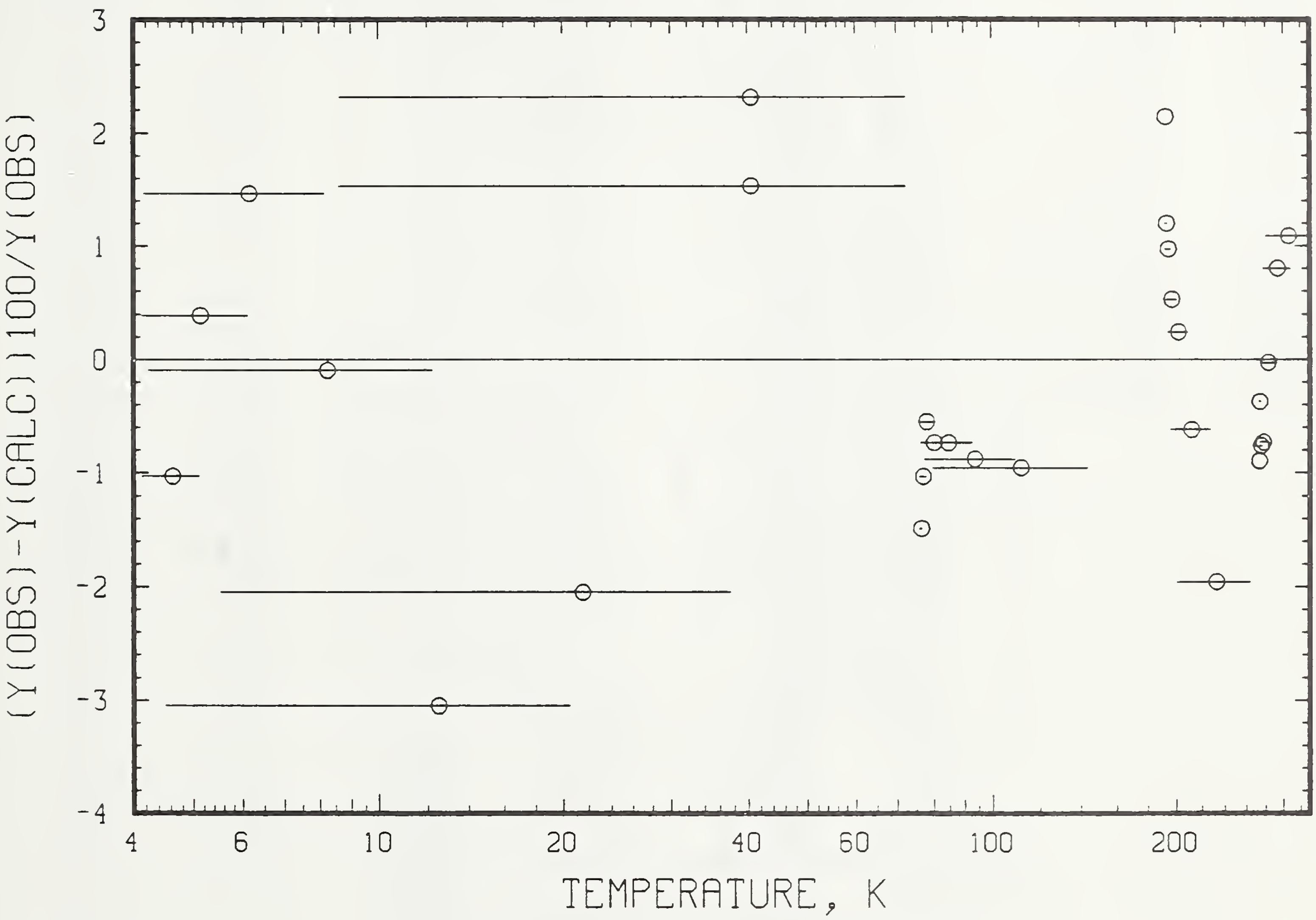



**Figure 7** Relative deviations of the experimental and calculated thermal conductivity integrals for specimen PK-Al-1-0°.

Table 13 Experimental Data for PK-Al-1-90°

| Average Temperature Kelvin | Thermal Conductivity W/(m·K) |
|---|---|
| 4.627 | 0.008 |
| 5.136 | 0.009 |
| 6.160 | 0.012 |
| 8.232 | 0.018 |
| 12.506 | 0.033 |
| 21.522 | 0.068 |
| 40.280 | 0.141 |
| 76.536 | 0.260 |
| 77.071 | 0.257 |
| 78.143 | 0.261 |
| 80.292 | 0.265 |
| 84.607 | 0.276 |
| 93.302 | 0.296 |
| 98.107 | 0.308 |
| 192.582 | 0.470 |
| 193.162 | 0.461 |
| 194.327 | 0.463 |
| 196.667 | 0.471 |
| 201.362 | 0.477 |
| 210.844 | 0.487 |
| 230.137 | 0.502 |
| 273.738 | 0.553 |
| 274.325 | 0.544 |
| 275.510 | 0.573 |
| 277.856 | 0.547 |
| 282.589 | 0.551 |
| 292.145 | 0.560 |
| 311.721 | 0.593 |

Table 14 Coefficients of $\lambda(T)$ for PK-Al-1-90°

| | |
|---|---|
| $a_1$ | 3.5119232E-03 |
| $a_2$ | 7.4568227E-03 |
| $a_3$ | -1.0401511E-02 |
| $a_4$ | 4.4786925E-03 |
| $a_5$ | -4.1507969E-04 |

Table 15 Thermal Conductivity Values as a Function of Temperature for Specimen PK-Al-1-90°

| T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) |
|---|---|---|---|---|---|---|---|
| 4.1000 | 0.0073 | 9.1000 | 0.0200 | 51.0000 | 0.1805 | 110.0000 | 0.3370 |
| 4.2000 | 0.0075 | 9.2000 | 0.0203 | 52.0000 | 0.1839 | 120.0000 | 0.3572 |
| 4.3000 | 0.0076 | 9.3000 | 0.0207 | 53.0000 | 0.1872 | 130.0000 | 0.3760 |
| 4.4000 | 0.0078 | 9.4000 | 0.0210 | 54.0000 | 0.1905 | 140.0000 | 0.3936 |
| 4.5000 | 0.0080 | 9.5000 | 0.0213 | 55.0000 | 0.1937 | 150.0000 | 0.4100 |
| 4.6000 | 0.0082 | 9.6000 | 0.0217 | 56.0000 | 0.1970 | 160.0000 | 0.4254 |
| 4.7000 | 0.0083 | 9.7000 | 0.0220 | 57.0000 | 0.2002 | 170.0000 | 0.4399 |
| 4.8000 | 0.0085 | 9.8000 | 0.0224 | 58.0000 | 0.2033 | 180.0000 | 0.4535 |
| 4.9000 | 0.0087 | 9.9000 | 0.0227 | 59.0000 | 0.2065 | 190.0000 | 0.4663 |
| 5.0000 | 0.0089 | 10.0000 | 0.0230 | 60.0000 | 0.2096 | 200.0000 | 0.4784 |
| 5.1000 | 0.0091 | 11.0000 | 0.0266 | 61.0000 | 0.2127 | 210.0000 | 0.4897 |
| 5.2000 | 0.0093 | 12.0000 | 0.0303 | 62.0000 | 0.2157 | 220.0000 | 0.5005 |
| 5.3000 | 0.0095 | 13.0000 | 0.0341 | 63.0000 | 0.2188 | 230.0000 | 0.5106 |
| 5.4000 | 0.0097 | 14.0000 | 0.0380 | 64.0000 | 0.2218 | 240.0000 | 0.5202 |
| 5.5000 | 0.0099 | 15.0000 | 0.0420 | 65.0000 | 0.2248 | 250.0000 | 0.5292 |
| 5.6000 | 0.0101 | 16.0000 | 0.0461 | 66.0000 | 0.2277 | 260.0000 | 0.5378 |
| 5.7000 | 0.0104 | 17.0000 | 0.0501 | 67.0000 | 0.2307 | 270.0000 | 0.5459 |
| 5.8000 | 0.0106 | 18.0000 | 0.0542 | 68.0000 | 0.2336 | 280.0000 | 0.5535 |
| 5.9000 | 0.0108 | 19.0000 | 0.0584 | 69.0000 | 0.2365 | 290.0000 | 0.5608 |
| 6.0000 | 0.0111 | 20.0000 | 0.0625 | 70.0000 | 0.2393 | 300.0000 | 0.5676 |
| 6.1000 | 0.0113 | 21.0000 | 0.0666 | 71.0000 | 0.2422 | 310.0000 | 0.5741 |
| 6.2000 | 0.0115 | 22.0000 | 0.0708 | 72.0000 | 0.2450 | 320.0000 | 0.5803 |
| 6.3000 | 0.0118 | 23.0000 | 0.0749 | 73.0000 | 0.2478 | 330.0000 | 0.5861 |
| 6.4000 | 0.0120 | 24.0000 | 0.0790 | 74.0000 | 0.2506 | 340.0000 | 0.5915 |
| 6.5000 | 0.0123 | 25.0000 | 0.0831 | 75.0000 | 0.2533 | | |
| 6.6000 | 0.0126 | 26.0000 | 0.0872 | 76.0000 | 0.2560 | | |
| 6.7000 | 0.0128 | 27.0000 | 0.0913 | 77.0000 | 0.2587 | | |
| 6.8000 | 0.0131 | 28.0000 | 0.0953 | 78.0000 | 0.2614 | | |
| 6.9000 | 0.0134 | 29.0000 | 0.0994 | 79.0000 | 0.2641 | | |
| 7.0000 | 0.0136 | 30.0000 | 0.1034 | 80.0000 | 0.2667 | | |
| 7.1000 | 0.0139 | 31.0000 | 0.1073 | 81.0000 | 0.2693 | | |
| 7.2000 | 0.0142 | 32.0000 | 0.1113 | 82.0000 | 0.2719 | | |
| 7.3000 | 0.0145 | 33.0000 | 0.1152 | 83.0000 | 0.2745 | | |
| 7.4000 | 0.0147 | 34.0000 | 0.1191 | 84.0000 | 0.2771 | | |
| 7.5000 | 0.0150 | 35.0000 | 0.1230 | 85.0000 | 0.2796 | | |
| 7.6000 | 0.0153 | 36.0000 | 0.1268 | 86.0000 | 0.2821 | | |
| 7.7000 | 0.0156 | 37.0000 | 0.1306 | 87.0000 | 0.2846 | | |
| 7.8000 | 0.0159 | 38.0000 | 0.1344 | 88.0000 | 0.2871 | | |
| 7.9000 | 0.0162 | 39.0000 | 0.1381 | 89.0000 | 0.2895 | | |
| 8.0000 | 0.0165 | 40.0000 | 0.1418 | 90.0000 | 0.2920 | | |
| 8.1000 | 0.0168 | 41.0000 | 0.1455 | 91.0000 | 0.2944 | | |
| 8.2000 | 0.0171 | 42.0000 | 0.1491 | 92.0000 | 0.2968 | | |
| 8.3000 | 0.0174 | 43.0000 | 0.1527 | 93.0000 | 0.2992 | | |
| 8.4000 | 0.0177 | 44.0000 | 0.1563 | 94.0000 | 0.3015 | | |
| 8.5000 | 0.0181 | 45.0000 | 0.1599 | 95.0000 | 0.3039 | | |
| 8.6000 | 0.0184 | 46.0000 | 0.1634 | 96.0000 | 0.3062 | | |
| 8.7000 | 0.0187 | 47.0000 | 0.1669 | 97.0000 | 0.3085 | | |
| 8.8000 | 0.0190 | 48.0000 | 0.1703 | 98.0000 | 0.3108 | | |
| 8.9000 | 0.0193 | 49.0000 | 0.1738 | 99.0000 | 0.3131 | | |
| 9.0000 | 0.0197 | 50.0000 | 0.1772 | 100.0000 | 0.3153 | | |

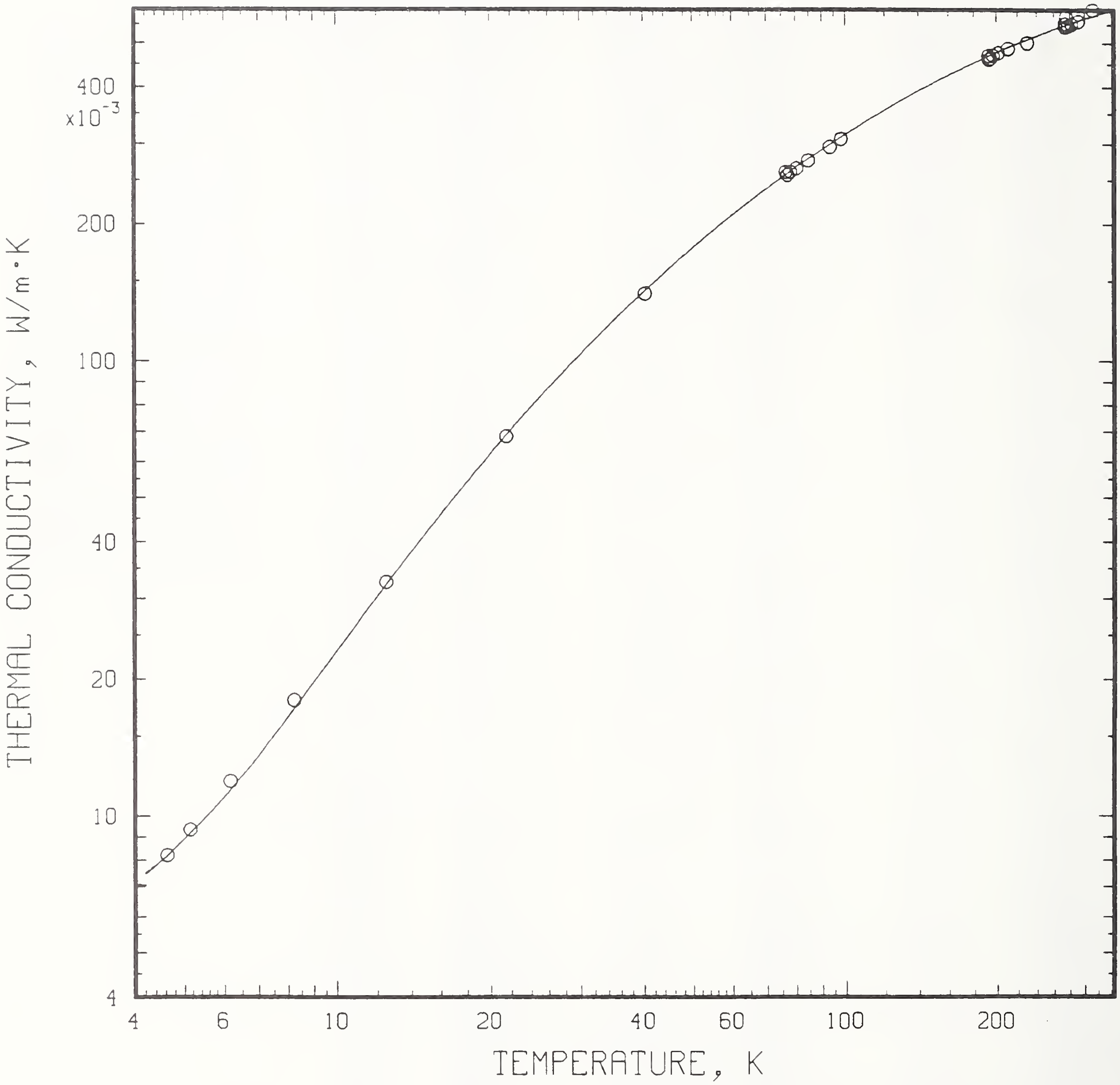



Figure 8 Thermal conductivity of specimen PK-Al-1-90°. Experimental data are presented as discrete points.

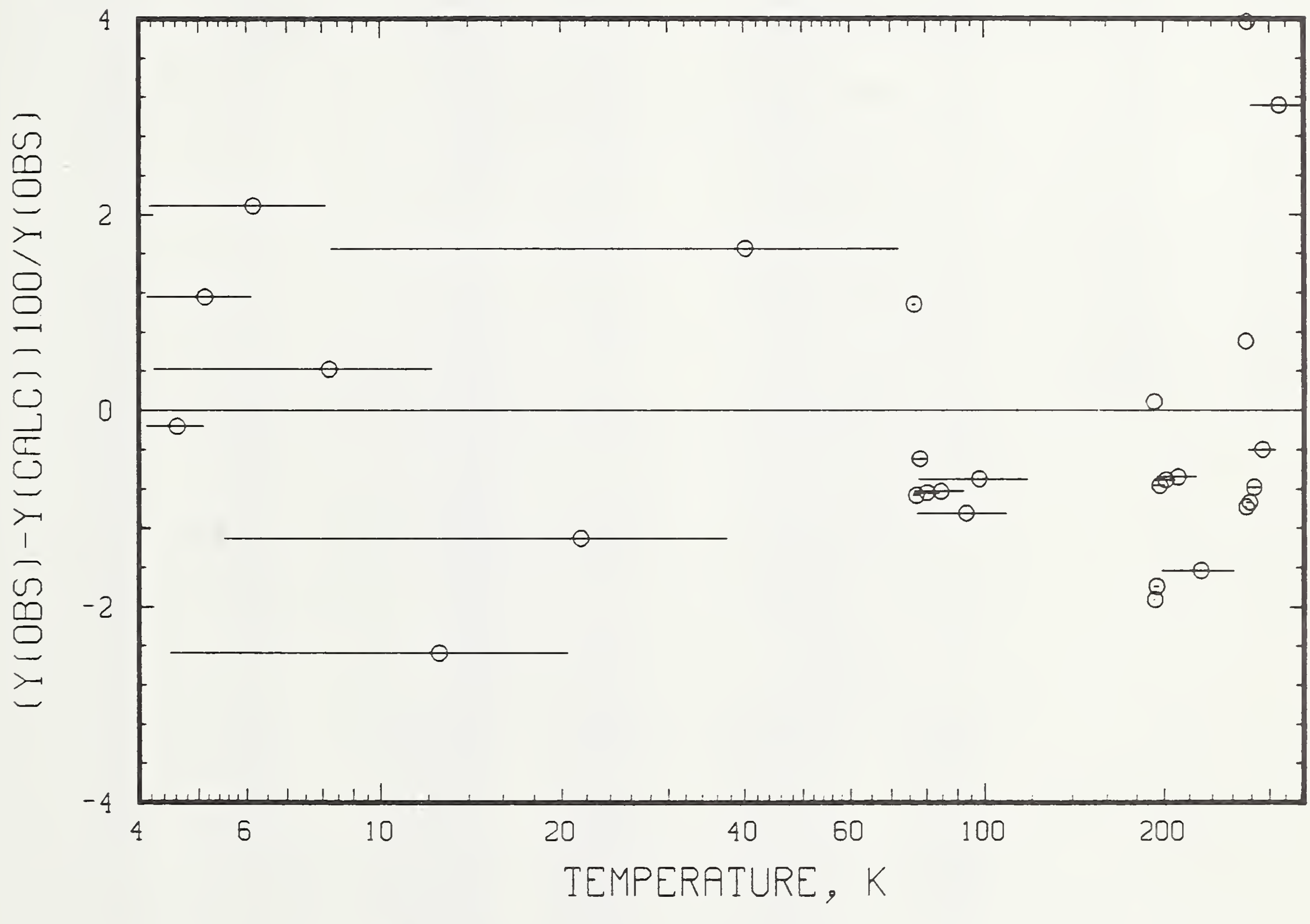



**Figure 9** Relative deviations of the experimental and calculated thermal conductivity integrals for specimen PK-Al-1-90°.

Table 16 Experimental Data for PK-Al-2-0°

| Average Temperature Kelvin | Thermal Conductivity W/(m·K) |
|---|---|
| 5.134 | 0.016 |
| 6.157 | 0.019 |
| 8.200 | 0.028 |
| 12.419 | 0.050 |
| 21.195 | 0.108 |
| 39.561 | 0.243 |
| 76.530 | 0.494 |
| 77.058 | 0.488 |
| 78.120 | 0.494 |
| 80.247 | 0.509 |
| 84.515 | 0.534 |
| 93.129 | 0.589 |
| 110.632 | 0.691 |
| 110.639 | 0.693 |
| 192.582 | 1.117 |
| 192.582 | 1.116 |
| 193.159 | 1.081 |
| 194.320 | 1.080 |
| 196.648 | 1.091 |
| 201.328 | 1.107 |
| 210.770 | 1.129 |
| 230.056 | 1.185 |
| 273.735 | 1.261 |
| 274.321 | 1.269 |
| 275.492 | 1.265 |
| 277.841 | 1.272 |
| 282.563 | 1.285 |
| 292.104 | 1.316 |
| 311.595 | 1.378 |

**Table 17** Coefficients of $\lambda(T)$ for PK-Al-2-0°

| | |
|---|---|
| $a_1$ | 1.9787333E-01 |
| $a_2$ | -3.4326128E-01 |
| $a_3$ | 2.3817078E-01 |
| $a_4$ | -8.0759153E-02 |
| $a_5$ | 1.3746504E-02 |
| $a_6$ | -8.8121097E-04 |

Table 18 Thermal Conductivity Values as a Function of Temperature for Specimen PK-Al-2-0°.

| T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) |
|---|---|---|---|---|---|---|---|
| 4.1000 | 0.0135 | 9.1000 | 0.0321 | 51.0000 | 0.3162 | 110.0000 | 0.7012 |
| 4.2000 | 0.0136 | 9.2000 | 0.0326 | 52.0000 | 0.3234 | 120.0000 | 0.7567 |
| 4.3000 | 0.0137 | 9.3000 | 0.0331 | 53.0000 | 0.3306 | 130.0000 | 0.8091 |
| 4.4000 | 0.0138 | 9.4000 | 0.0336 | 54.0000 | 0.3378 | 140.0000 | 0.8587 |
| 4.5000 | 0.0139 | 9.5000 | 0.0342 | 55.0000 | 0.3449 | 150.0000 | 0.9054 |
| 4.6000 | 0.0141 | 9.6000 | 0.0347 | 56.0000 | 0.3520 | 160.0000 | 0.9494 |
| 4.7000 | 0.0143 | 9.7000 | 0.0352 | 57.0000 | 0.3592 | 170.0000 | 0.9908 |
| 4.8000 | 0.0145 | 9.8000 | 0.0358 | 58.0000 | 0.3663 | 180.0000 | 1.0295 |
| 4.9000 | 0.0147 | 9.9000 | 0.0363 | 59.0000 | 0.3733 | 190.0000 | 1.0658 |
| 5.0000 | 0.0149 | 10.0000 | 0.0368 | 60.0000 | 0.3804 | 200.0000 | 1.0998 |
| 5.1000 | 0.0151 | 11.0000 | 0.0423 | 61.0000 | 0.3875 | 210.0000 | 1.1314 |
| 5.2000 | 0.0154 | 12.0000 | 0.0480 | 62.0000 | 0.3945 | 220.0000 | 1.1608 |
| 5.3000 | 0.0157 | 13.0000 | 0.0538 | 63.0000 | 0.4015 | 230.0000 | 1.1881 |
| 5.4000 | 0.0160 | 14.0000 | 0.0597 | 64.0000 | 0.4085 | 240.0000 | 1.2133 |
| 5.5000 | 0.0163 | 15.0000 | 0.0658 | 65.0000 | 0.4155 | 250.0000 | 1.2366 |
| 5.6000 | 0.0166 | 16.0000 | 0.0719 | 66.0000 | 0.4224 | 260.0000 | 1.2580 |
| 5.7000 | 0.0169 | 17.0000 | 0.0781 | 67.0000 | 0.4293 | 270.0000 | 1.2775 |
| 5.8000 | 0.0172 | 18.0000 | 0.0844 | 68.0000 | 0.4362 | 280.0000 | 1.2952 |
| 5.9000 | 0.0176 | 19.0000 | 0.0908 | 69.0000 | 0.4431 | 290.0000 | 1.3113 |
| 6.0000 | 0.0179 | 20.0000 | 0.0973 | 70.0000 | 0.4499 | 300.0000 | 1.3257 |
| 6.1000 | 0.0183 | 21.0000 | 0.1039 | 71.0000 | 0.4568 | 310.0000 | 1.3384 |
| 6.2000 | 0.0187 | 22.0000 | 0.1105 | 72.0000 | 0.4636 | 320.0000 | 1.3497 |
| 6.3000 | 0.0191 | 23.0000 | 0.1172 | 73.0000 | 0.4703 | 330.0000 | 1.3595 |
| 6.4000 | 0.0195 | 24.0000 | 0.1239 | 74.0000 | 0.4771 | 340.0000 | 1.3678 |
| 6.5000 | 0.0199 | 25.0000 | 0.1307 | 75.0000 | 0.4838 | | |
| 6.6000 | 0.0203 | 26.0000 | 0.1375 | 76.0000 | 0.4905 | | |
| 6.7000 | 0.0207 | 27.0000 | 0.1444 | 77.0000 | 0.4972 | | |
| 6.8000 | 0.0211 | 28.0000 | 0.1514 | 78.0000 | 0.5038 | | |
| 6.9000 | 0.0215 | 29.0000 | 0.1583 | 79.0000 | 0.5105 | | |
| 7.0000 | 0.0220 | 30.0000 | 0.1653 | 80.0000 | 0.5170 | | |
| 7.1000 | 0.0224 | 31.0000 | 0.1724 | 81.0000 | 0.5236 | | |
| 7.2000 | 0.0228 | 32.0000 | 0.1795 | 82.0000 | 0.5301 | | |
| 7.3000 | 0.0233 | 33.0000 | 0.1866 | 83.0000 | 0.5367 | | |
| 7.4000 | 0.0237 | 34.0000 | 0.1937 | 84.0000 | 0.5431 | | |
| 7.5000 | 0.0242 | 35.0000 | 0.2008 | 85.0000 | 0.5496 | | |
| 7.6000 | 0.0247 | 36.0000 | 0.2080 | 86.0000 | 0.5560 | | |
| 7.7000 | 0.0251 | 37.0000 | 0.2152 | 87.0000 | 0.5624 | | |
| 7.8000 | 0.0256 | 38.0000 | 0.2224 | 88.0000 | 0.5688 | | |
| 7.9000 | 0.0261 | 39.0000 | 0.2296 | 89.0000 | 0.5751 | | |
| 8.0000 | 0.0266 | 40.0000 | 0.2368 | 90.0000 | 0.5814 | | |
| 8.1000 | 0.0270 | 41.0000 | 0.2440 | 91.0000 | 0.5877 | | |
| 8.2000 | 0.0275 | 42.0000 | 0.2512 | 92.0000 | 0.5939 | | |
| 8.3000 | 0.0280 | 43.0000 | 0.2585 | 93.0000 | 0.6001 | | |
| 8.4000 | 0.0285 | 44.0000 | 0.2657 | 94.0000 | 0.6063 | | |
| 8.5000 | 0.0290 | 45.0000 | 0.2729 | 95.0000 | 0.6125 | | |
| 8.6000 | 0.0295 | 46.0000 | 0.2802 | 96.0000 | 0.6186 | | |
| 8.7000 | 0.0300 | 47.0000 | 0.2874 | 97.0000 | 0.6247 | | |
| 8.8000 | 0.0305 | 48.0000 | 0.2946 | 98.0000 | 0.6308 | | |
| 8.9000 | 0.0310 | 49.0000 | 0.3018 | 99.0000 | 0.6368 | | |
| 9.0000 | 0.0316 | 50.0000 | 0.3090 | 100.0000 | 0.6428 | | |

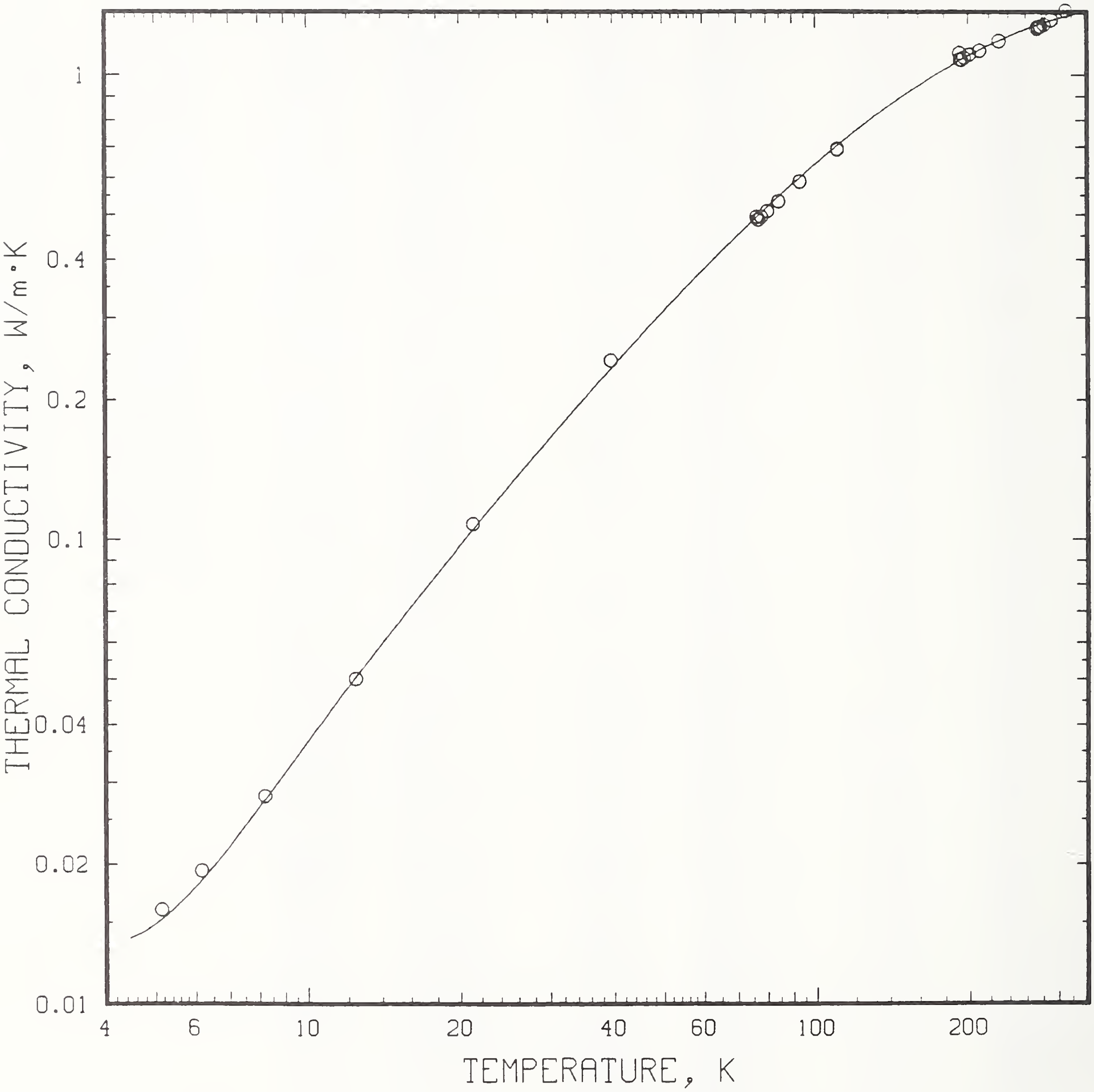



**Figure 10** Thermal conductivity of specimen PK-Al-2-0°. Experimental data are presented as discrete points.

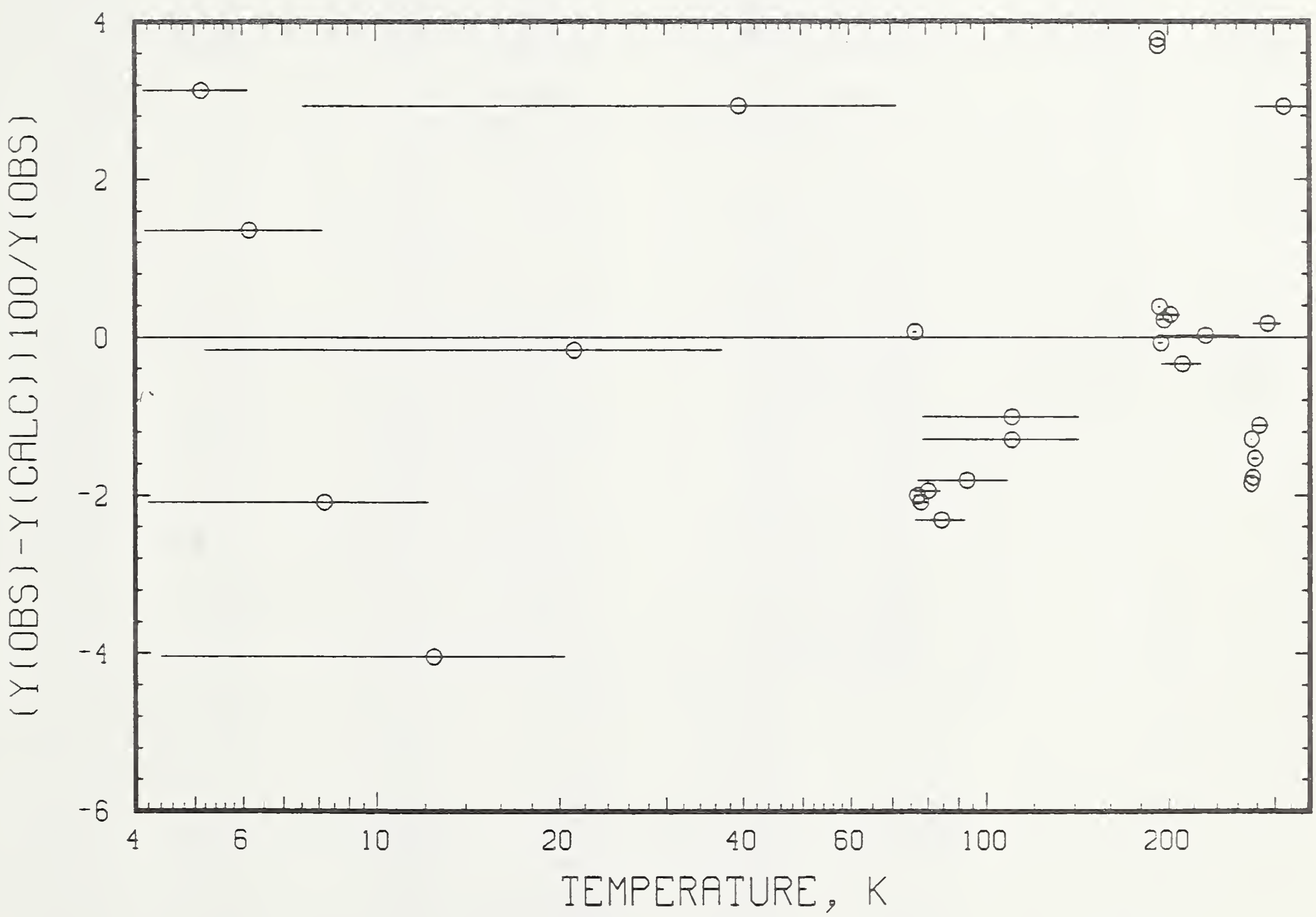



**Figure 11** Relative deviations of the experimental and calculated thermal conductivity integrals for specimen PK-Al-2-0°.

Table 19 Experimental Data for Neat-PK

| Average Temperature Kelvin | Thermal Conductivity W/(m·K) |
|---|---|
| 4.629 | 0.012 |
| 5.140 | 0.013 |
| 6.167 | 0.016 |
| 8.263 | 0.024 |
| 12.583 | 0.039 |
| 21.553 | 0.067 |
| 76.525 | 0.147 |
| 77.050 | 0.150 |
| 78.100 | 0.151 |
| 80.205 | 0.155 |
| 84.420 | 0.158 |
| 92.888 | 0.165 |
| 109.955 | 0.178 |
| 192.553 | 0.226 |
| 193.109 | 0.238 |
| 194.221 | 0.242 |
| 196.444 | 0.240 |
| 200.909 | 0.242 |
| 209.898 | 0.243 |
| 228.143 | 0.246 |
| 273.711 | 0.264 |
| 274.273 | 0.269 |
| 275.398 | 0.268 |
| 277.652 | 0.270 |
| 282.180 | 0.272 |
| 291.313 | 0.277 |
| 309.916 | 0.288 |

Table 20 Coefficients of $\lambda(T)$ for Neat-PK

| | |
|---|---|
| $a_1$ | 1.0636976E-01 |
| $a_2$ | -1.6340006E-01 |
| $a_3$ | 9.4941322E-02 |
| $a_4$ | -2.4117988E-02 |
| $a_5$ | 2.8797748E-03 |
| $a_6$ | -1.3025208E-04 |

Table 21 Thermal Conductivity Values as a Function of Temperature for Specimen Neat-PK.

| T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) | T Kelvin | λ(T) W/(m·K) |
|---|---|---|---|---|---|---|---|
| 4.1000 | 0.0108 | 9.1000 | 0.0271 | 51.0000 | 0.1252 | 110.0000 | 0.1801 |
| 4.2000 | 0.0110 | 9.2000 | 0.0275 | 52.0000 | 0.1265 | 120.0000 | 0.1871 |
| 4.3000 | 0.0111 | 9.3000 | 0.0279 | 53.0000 | 0.1277 | 130.0000 | 0.1938 |
| 4.4000 | 0.0112 | 9.4000 | 0.0283 | 54.0000 | 0.1290 | 140.0000 | 0.2003 |
| 4.5000 | 0.0114 | 9.5000 | 0.0287 | 55.0000 | 0.1302 | 150.0000 | 0.2065 |
| 4.6000 | 0.0116 | 9.6000 | 0.0291 | 56.0000 | 0.1314 | 160.0000 | 0.2124 |
| 4.7000 | 0.0118 | 9.7000 | 0.0295 | 57.0000 | 0.1326 | 170.0000 | 0.2182 |
| 4.8000 | 0.0120 | 9.8000 | 0.0299 | 58.0000 | 0.1338 | 180.0000 | 0.2239 |
| 4.9000 | 0.0122 | 9.9000 | 0.0303 | 59.0000 | 0.1349 | 190.0000 | 0.2293 |
| 5.0000 | 0.0124 | 10.0000 | 0.0307 | 60.0000 | 0.1361 | 200.0000 | 0.2347 |
| 5.1000 | 0.0127 | 11.0000 | 0.0347 | 61.0000 | 0.1372 | 210.0000 | 0.2399 |
| 5.2000 | 0.0129 | 12.0000 | 0.0387 | 62.0000 | 0.1383 | 220.0000 | 0.2450 |
| 5.3000 | 0.0132 | 13.0000 | 0.0425 | 63.0000 | 0.1394 | 230.0000 | 0.2499 |
| 5.4000 | 0.0135 | 14.0000 | 0.0462 | 64.0000 | 0.1405 | 240.0000 | 0.2548 |
| 5.5000 | 0.0138 | 15.0000 | 0.0498 | 65.0000 | 0.1415 | 250.0000 | 0.2596 |
| 5.6000 | 0.0140 | 16.0000 | 0.0533 | 66.0000 | 0.1426 | 260.0000 | 0.2642 |
| 5.7000 | 0.0143 | 17.0000 | 0.0566 | 67.0000 | 0.1436 | 270.0000 | 0.2688 |
| 5.8000 | 0.0147 | 18.0000 | 0.0598 | 68.0000 | 0.1446 | 280.0000 | 0.2733 |
| 5.9000 | 0.0150 | 19.0000 | 0.0629 | 69.0000 | 0.1457 | 290.0000 | 0.2777 |
| 6.0000 | 0.0153 | 20.0000 | 0.0659 | 70.0000 | 0.1467 | 300.0000 | 0.2821 |
| 6.1000 | 0.0156 | 21.0000 | 0.0688 | 71.0000 | 0.1476 | 310.0000 | 0.2863 |
| 6.2000 | 0.0160 | 22.0000 | 0.0716 | 72.0000 | 0.1486 | 320.0000 | 0.2905 |
| 6.3000 | 0.0163 | 23.0000 | 0.0743 | 73.0000 | 0.1496 | 330.0000 | 0.2946 |
| 6.4000 | 0.0166 | 24.0000 | 0.0769 | 74.0000 | 0.1505 | 340.0000 | 0.2986 |
| 6.5000 | 0.0170 | 25.0000 | 0.0794 | 75.0000 | 0.1515 | | |
| 6.6000 | 0.0173 | 26.0000 | 0.0818 | 76.0000 | 0.1524 | | |
| 6.7000 | 0.0177 | 27.0000 | 0.0842 | 77.0000 | 0.1534 | | |
| 6.8000 | 0.0181 | 28.0000 | 0.0864 | 78.0000 | 0.1543 | | |
| 6.9000 | 0.0184 | 29.0000 | 0.0887 | 79.0000 | 0.1552 | | |
| 7.0000 | 0.0188 | 30.0000 | 0.0908 | 80.0000 | 0.1561 | | |
| 7.1000 | 0.0192 | 31.0000 | 0.0929 | 81.0000 | 0.1570 | | |
| 7.2000 | 0.0196 | 32.0000 | 0.0949 | 82.0000 | 0.1579 | | |
| 7.3000 | 0.0199 | 33.0000 | 0.0969 | 83.0000 | 0.1587 | | |
| 7.4000 | 0.0203 | 34.0000 | 0.0988 | 84.0000 | 0.1596 | | |
| 7.5000 | 0.0207 | 35.0000 | 0.1006 | 85.0000 | 0.1605 | | |
| 7.6000 | 0.0211 | 36.0000 | 0.1024 | 86.0000 | 0.1613 | | |
| 7.7000 | 0.0215 | 37.0000 | 0.1042 | 87.0000 | 0.1622 | | |
| 7.8000 | 0.0219 | 38.0000 | 0.1059 | 88.0000 | 0.1630 | | |
| 7.9000 | 0.0223 | 39.0000 | 0.1076 | 89.0000 | 0.1639 | | |
| 8.0000 | 0.0227 | 40.0000 | 0.1092 | 90.0000 | 0.1647 | | |
| 8.1000 | 0.0231 | 41.0000 | 0.1109 | 91.0000 | 0.1655 | | |
| 8.2000 | 0.0235 | 42.0000 | 0.1124 | 92.0000 | 0.1663 | | |
| 8.3000 | 0.0239 | 43.0000 | 0.1140 | 93.0000 | 0.1671 | | |
| 8.4000 | 0.0243 | 44.0000 | 0.1155 | 94.0000 | 0.1679 | | |
| 8.5000 | 0.0247 | 45.0000 | 0.1169 | 95.0000 | 0.1687 | | |
| 8.6000 | 0.0251 | 46.0000 | 0.1184 | 96.0000 | 0.1695 | | |
| 8.7000 | 0.0255 | 47.0000 | 0.1198 | 97.0000 | 0.1703 | | |
| 8.8000 | 0.0259 | 48.0000 | 0.1212 | 98.0000 | 0.1711 | | |
| 8.9000 | 0.0263 | 49.0000 | 0.1225 | 99.0000 | 0.1719 | | |
| 9.0000 | 0.0267 | 50.0000 | 0.1239 | 100.0000 | 0.1726 | | |

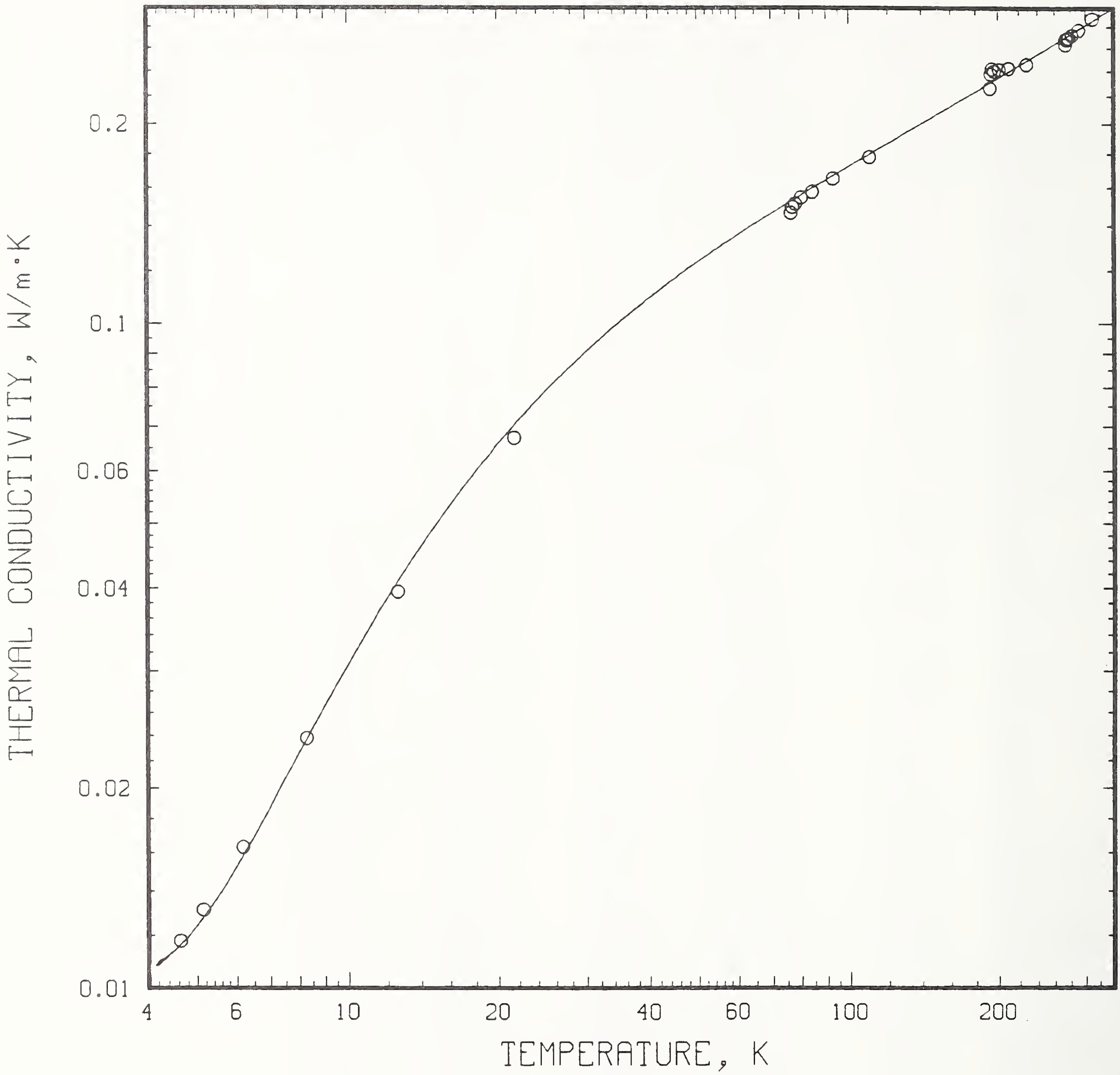



Figure 12 Thermal conductivity of specimen Neat-PK. Experimental data are presented as discrete points.

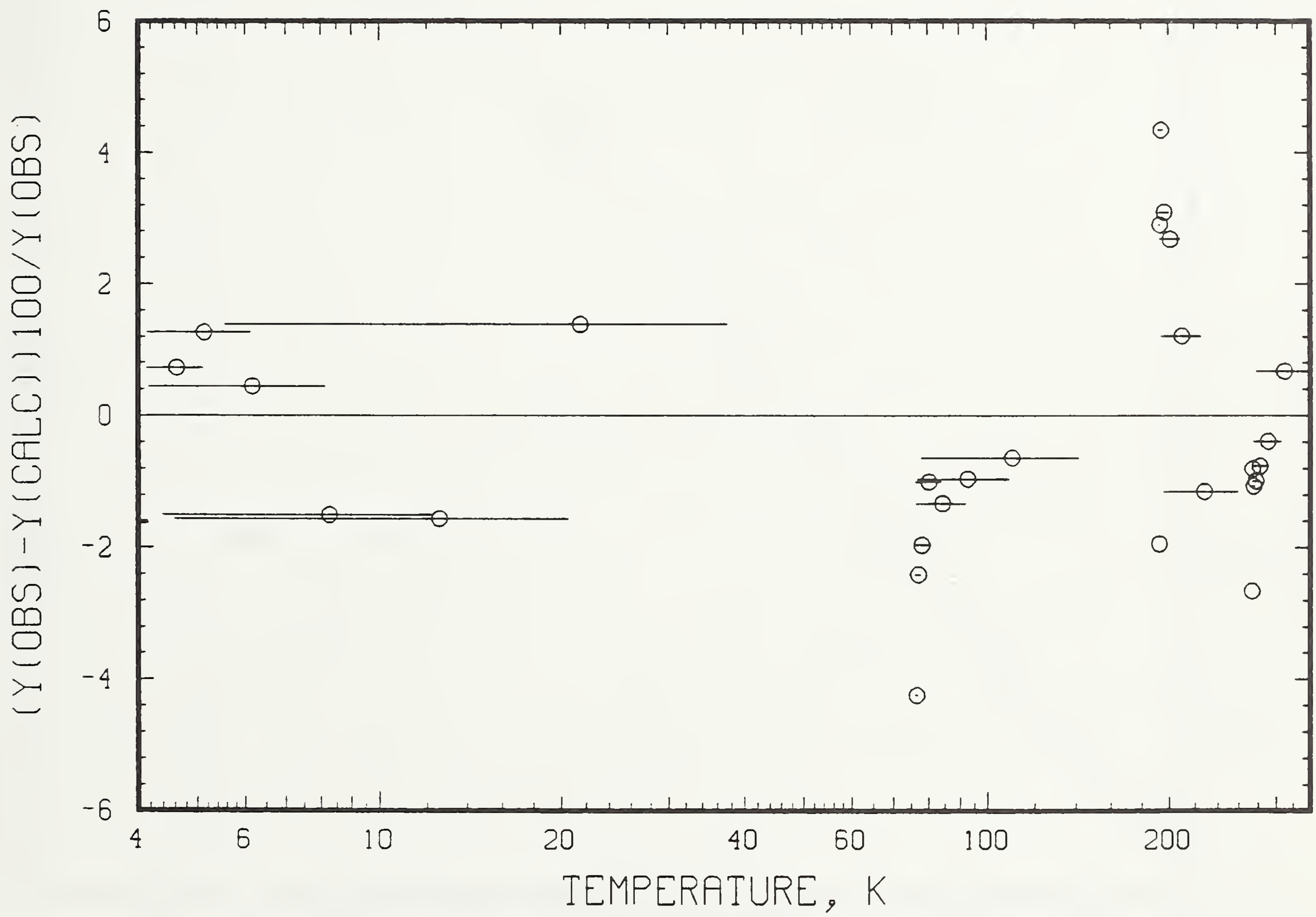



**Figure 13** Relative deviations of the experimental and calculated thermal conductivity integrals for specimen Neat-PK.

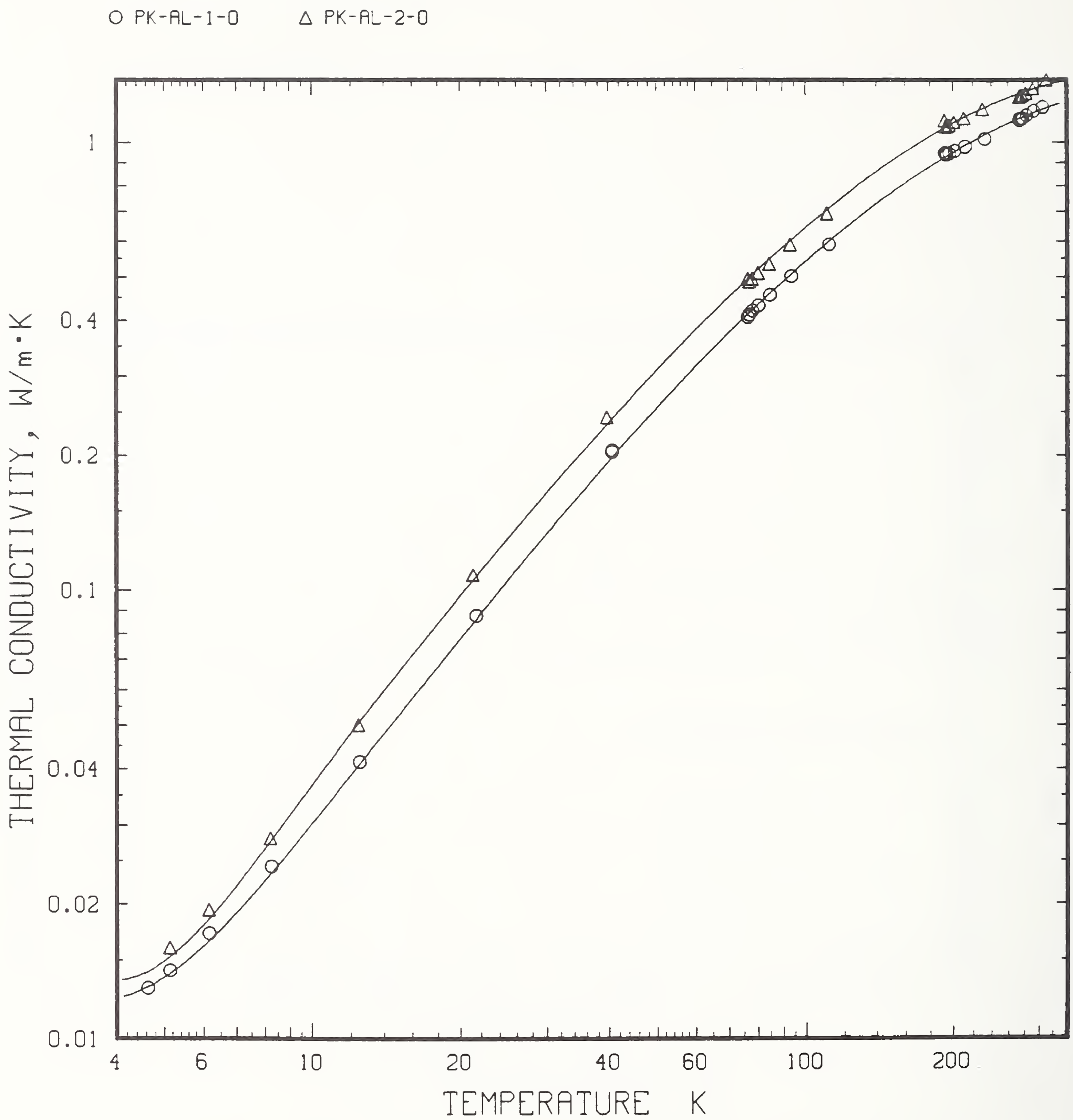



**Figure 14** Thermal conductivity of PK-Al-1-0° and PK-Al-2-0° specimens where heat is flowing parallel to the alumina fibers.

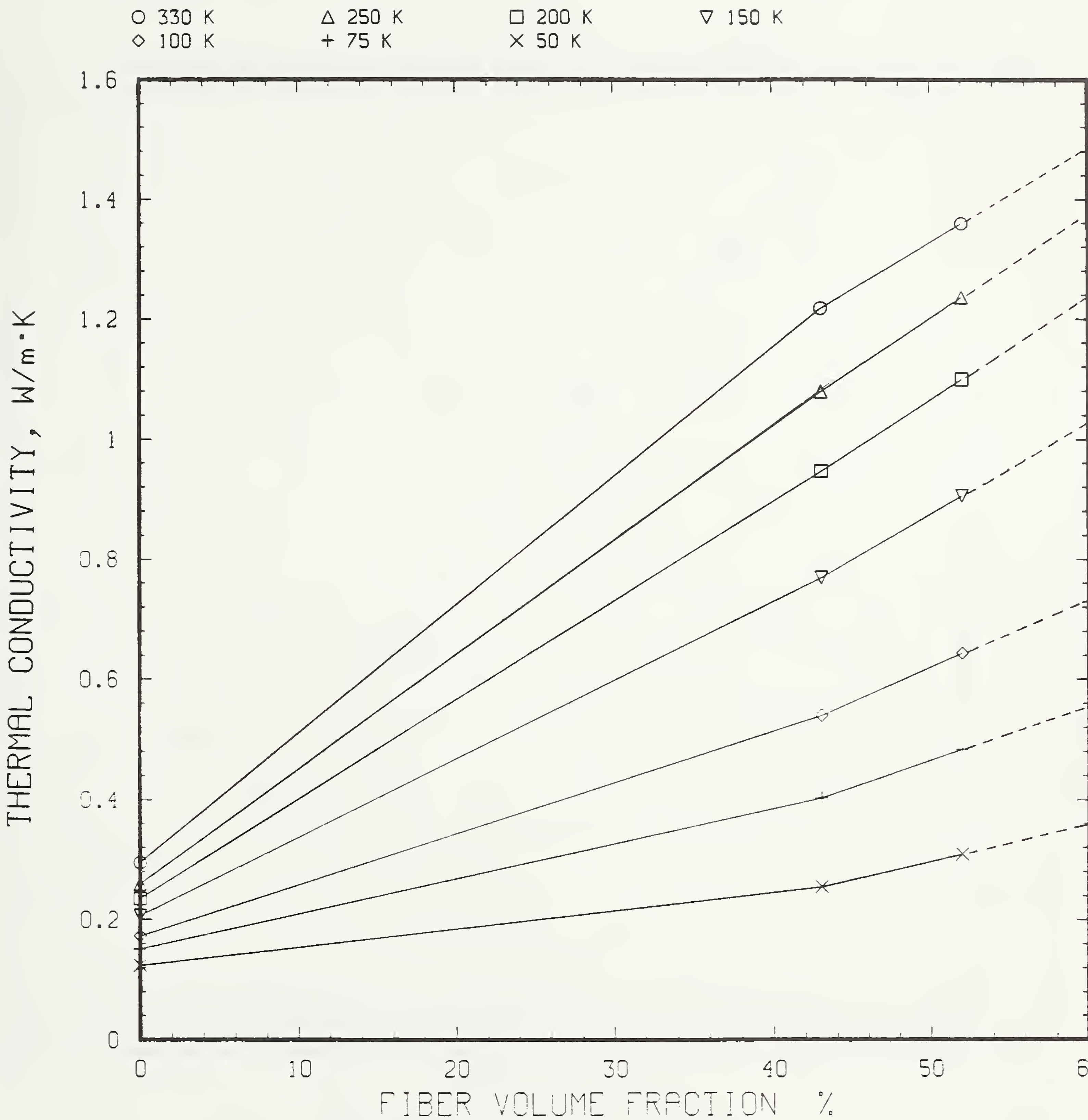



**Figure 15** Thermal conductivity as a function of fiber volume ratios for various calculated temperatures (above 40 K). The dashed line shows linear extrapolation taken.

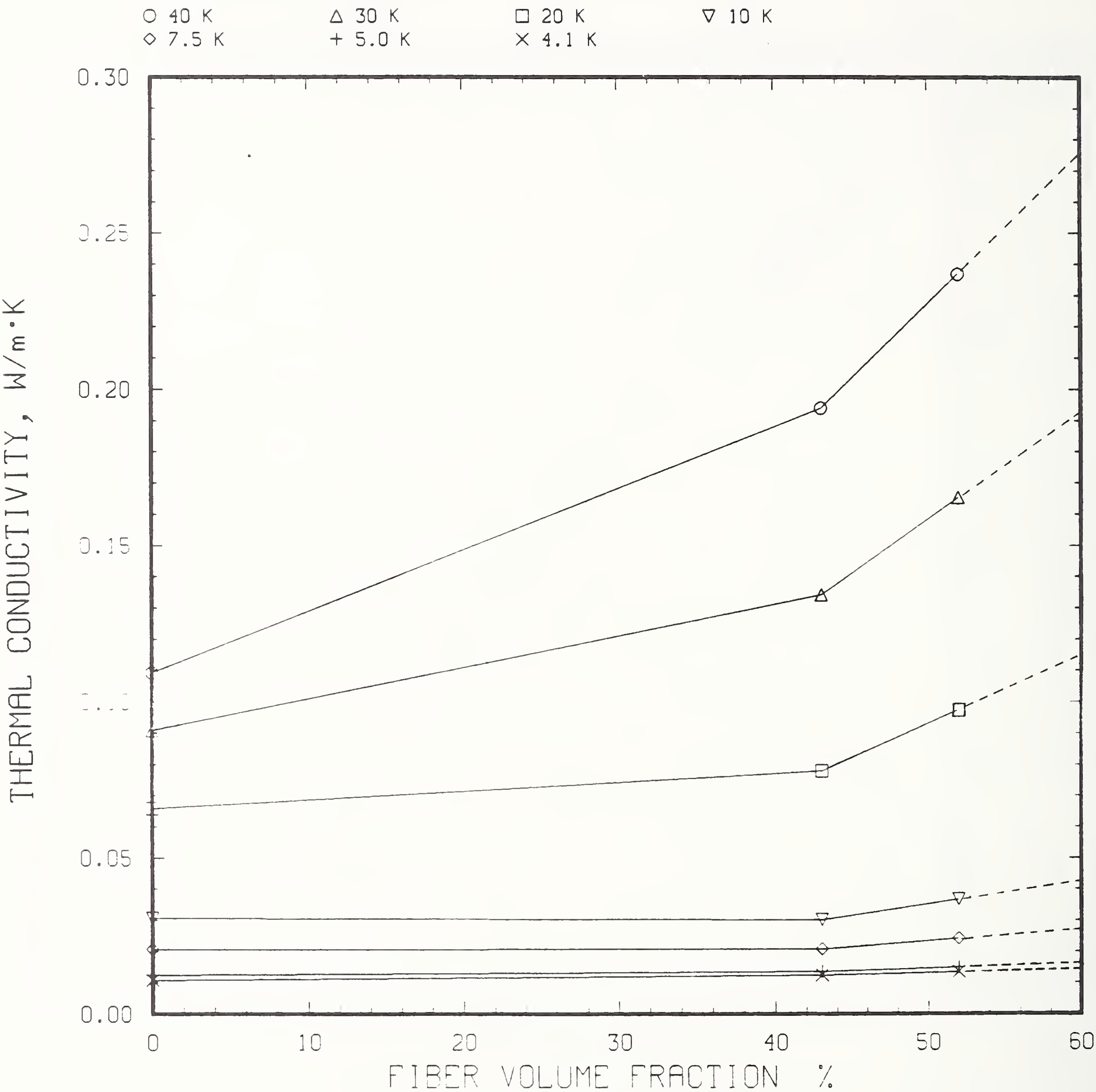



**Figure 16** Thermal conductivity as a function of fiber volume ratios for various calculated temperatures (below 40 K). The dashed line shows linear extrapolation taken.

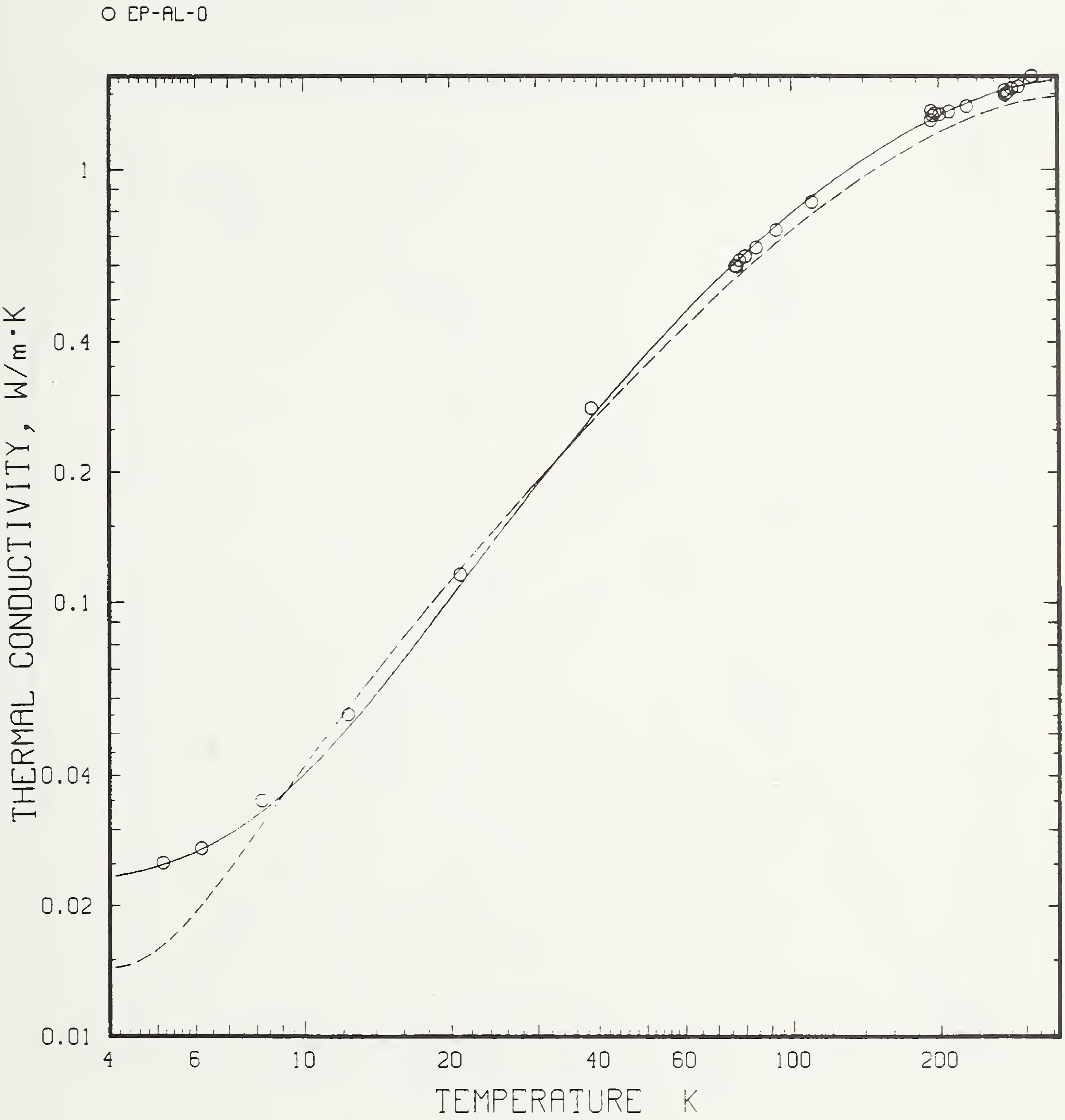



**Figure 17** Thermal conductivity as a function of temperature for the EP-Al-0° and the calculated PEEK/alumina curve (----). Comparison for the same fiber volume fraction. Note that both scales are logarithmic, which clarifies the behavior at low temperatures. Compare to Figure 18.

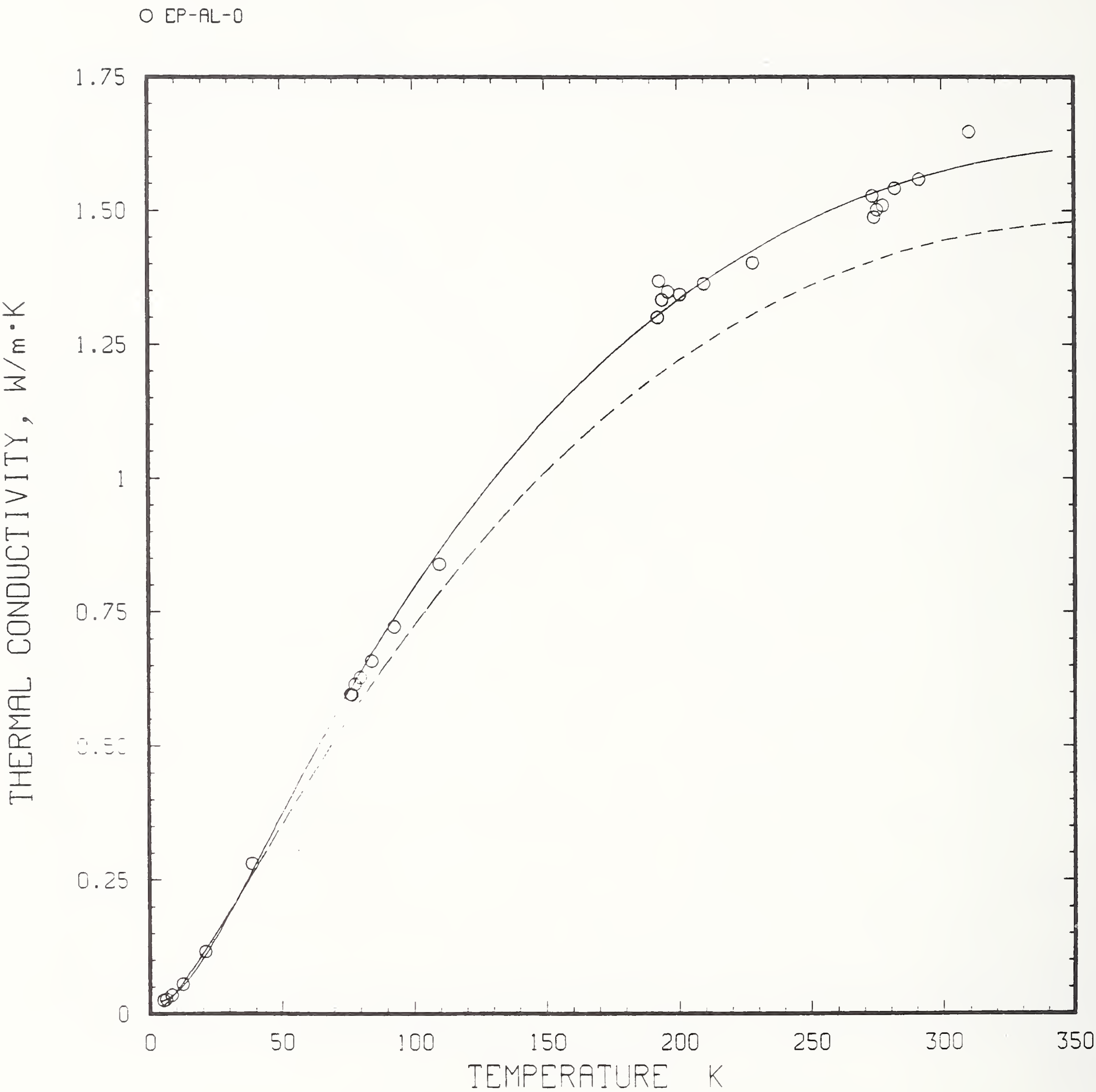



**Figure 18** Thermal conductivity as a function of temperature for the EP-Al-0° and the calculated PEEK/alumina curve (----). Comparison for the same fiber volume fraction. Note that both scales are linear, which clarifies the behavior at high temperatures. Compare to Figure 17.

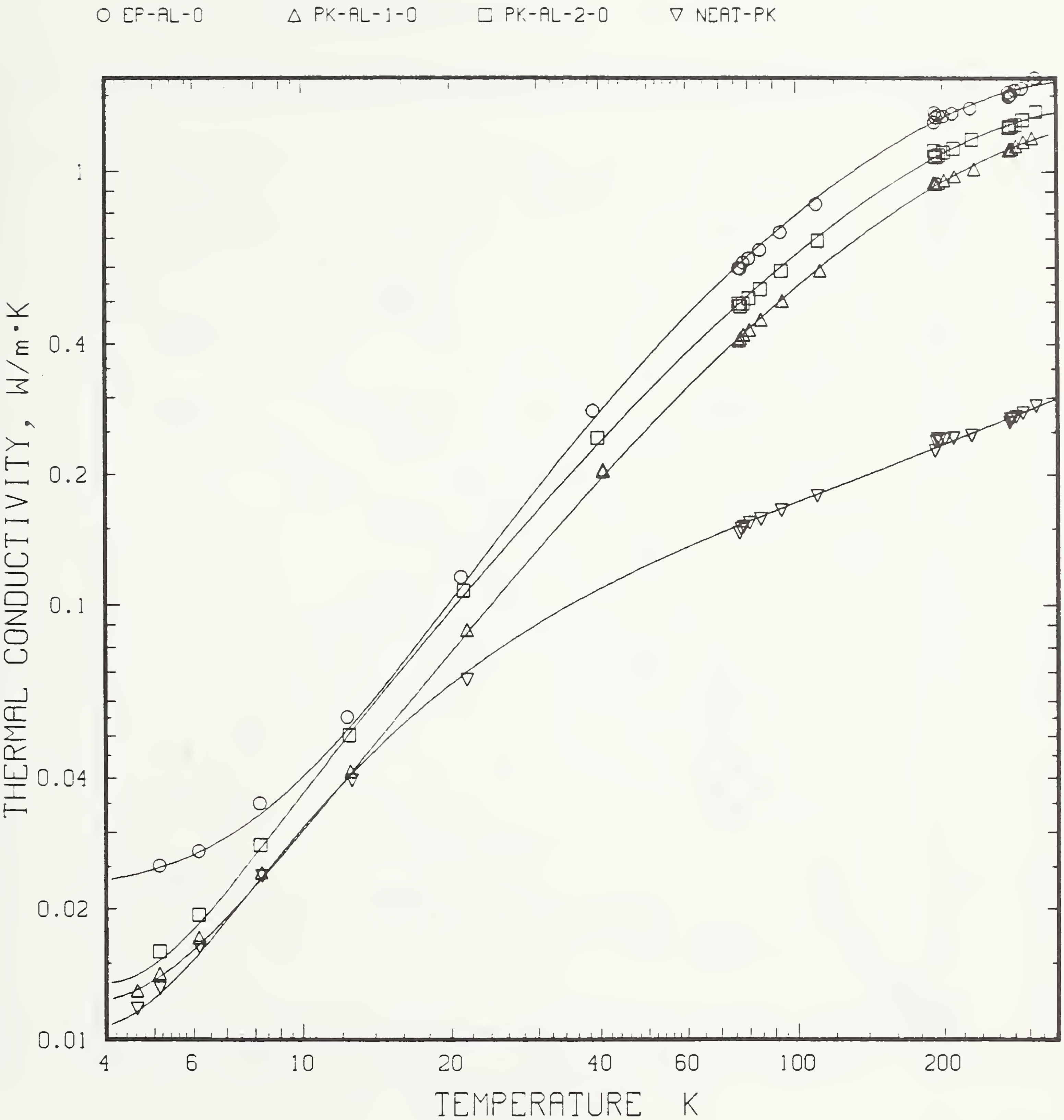



**Figure 19** Thermal conductivity of the specimens where heat is flowing parallel to the alumina fibers. The Neat-PEEK data are also included as a reference. Note that both scales are logarithmic, which clarifies the behavior at low temperatures. Compare to Figure 20.

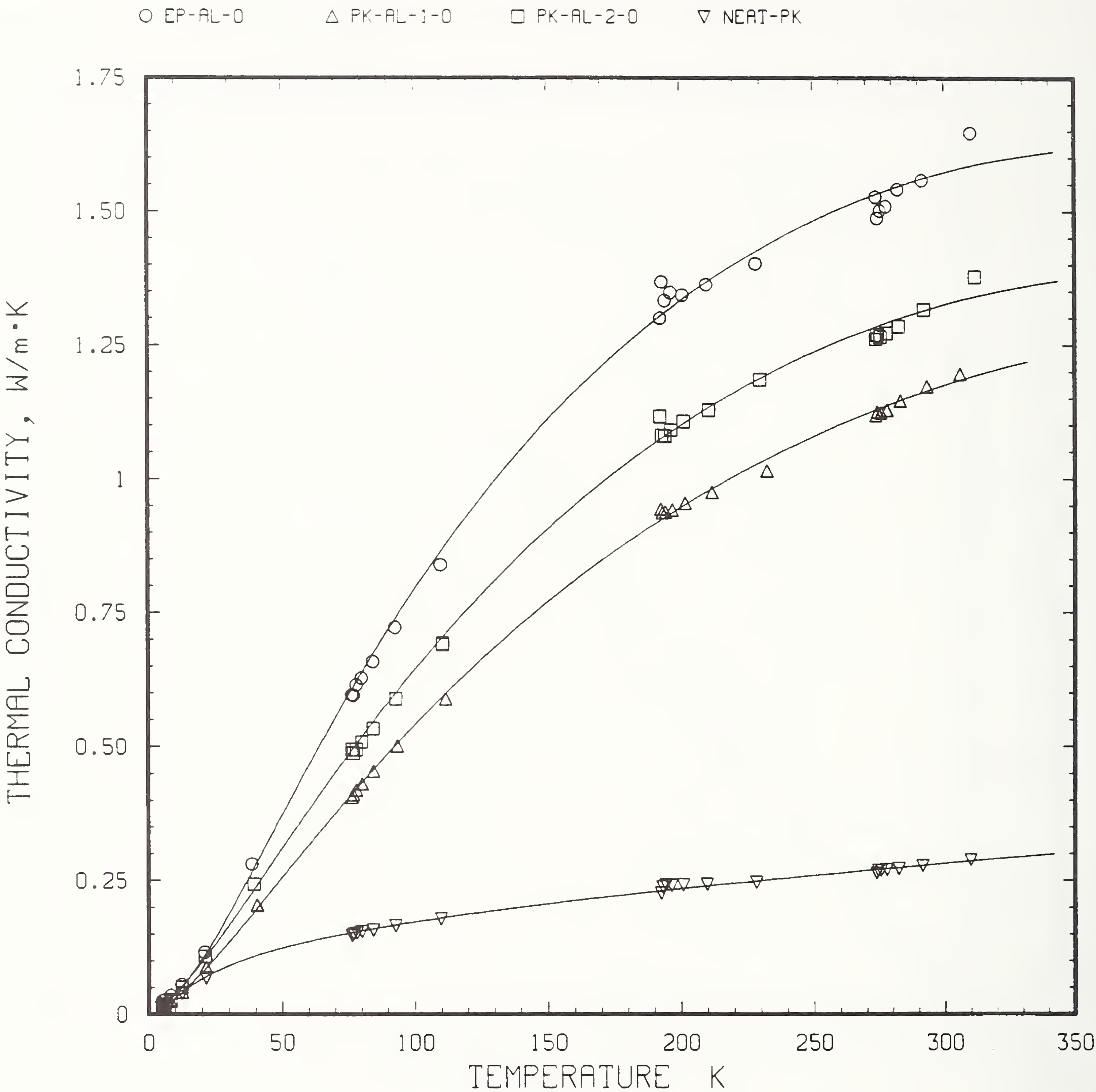



Figure 20 Thermal conductivity of the specimens where heat is flowing parallel to the alumina fibers. The Neat-PEEK data are also included as a reference. Note that both scales are linear, which clarifies the behavior at high temperatures. Compare to Figure 19.

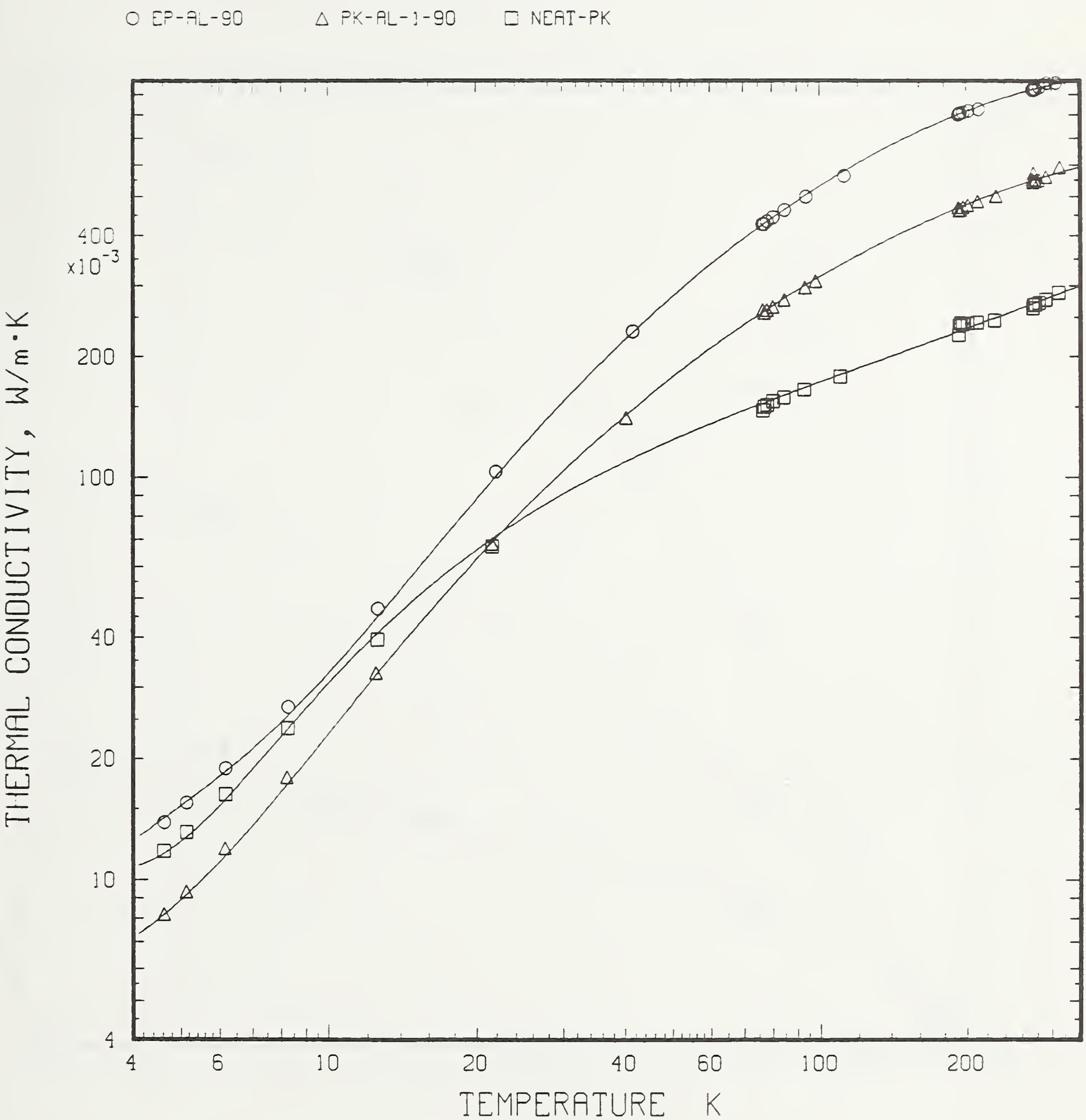



**Figure 21** Thermal conductivity of the specimens where heat is flowing perpendicular to the alumina fibers. The Neat-PEEK data are also included as a reference. Note that both scales are logarithmic, which clarifies the behavior at low temperatures. Compare to Figure 22.

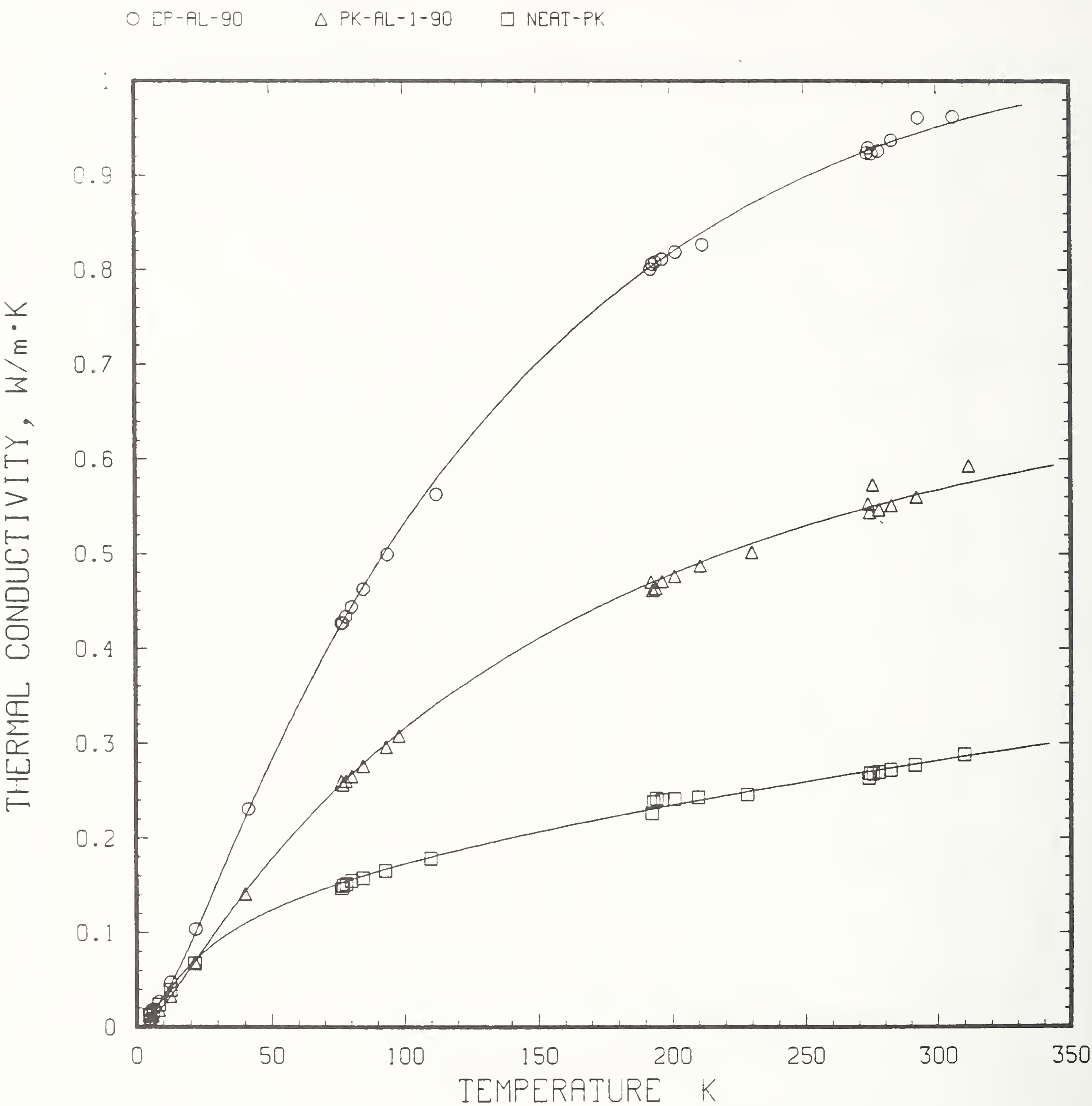



Figure 22 Thermal conductivity of the specimens where heat is flowing perpendicular to the alumina fibers. The Neat-PEEK data are also included as a reference. Note that both scales are linear, which clarifies the behavior at high temperatures. Compare to Figure 21.

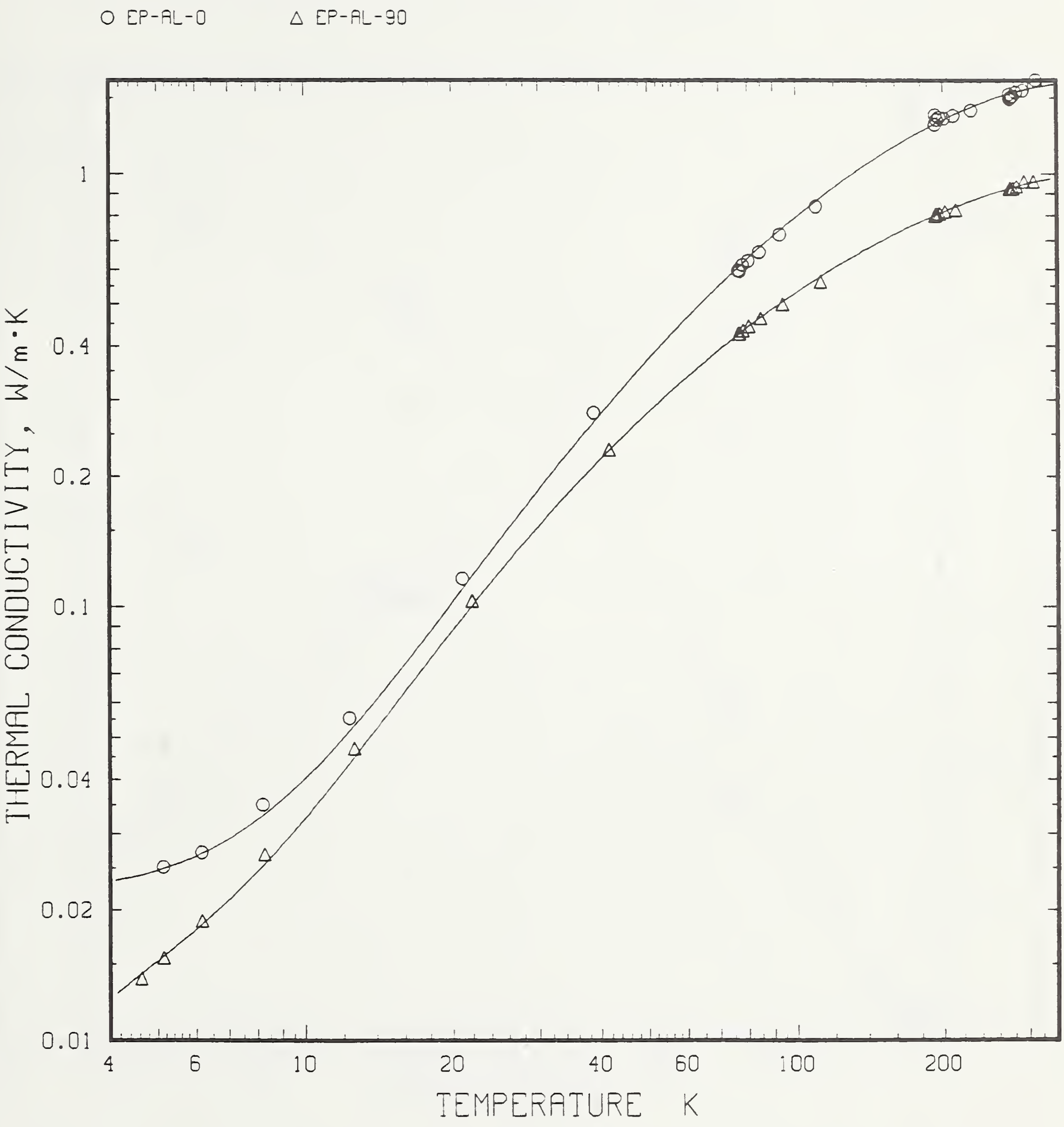



**Figure 23** Thermal conductivity of the epoxy/alumina fibered data, both parallel and perpendicular to alumina fibers. Note that both scales are logarithmic, which clarifies the behavior at low temperatures. Compare to Figure 24.

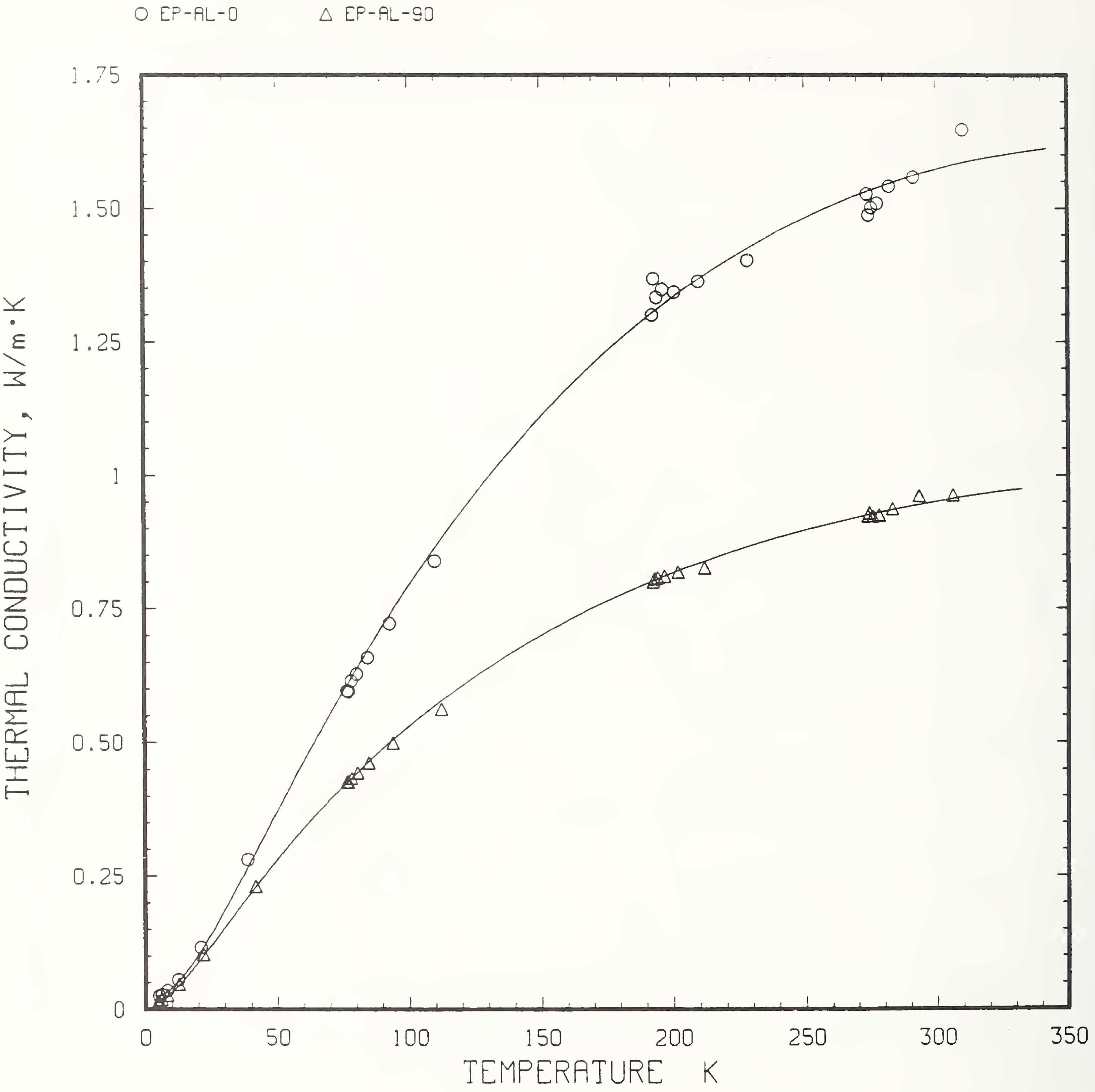



**Figure 24** Thermal conductivity of the epoxy/alumina fibered data, both parallel and perpendicular to alumina fibers. Note that both scales are linear, which clarifies the behavior at high temperatures. Compare to Figure 23.

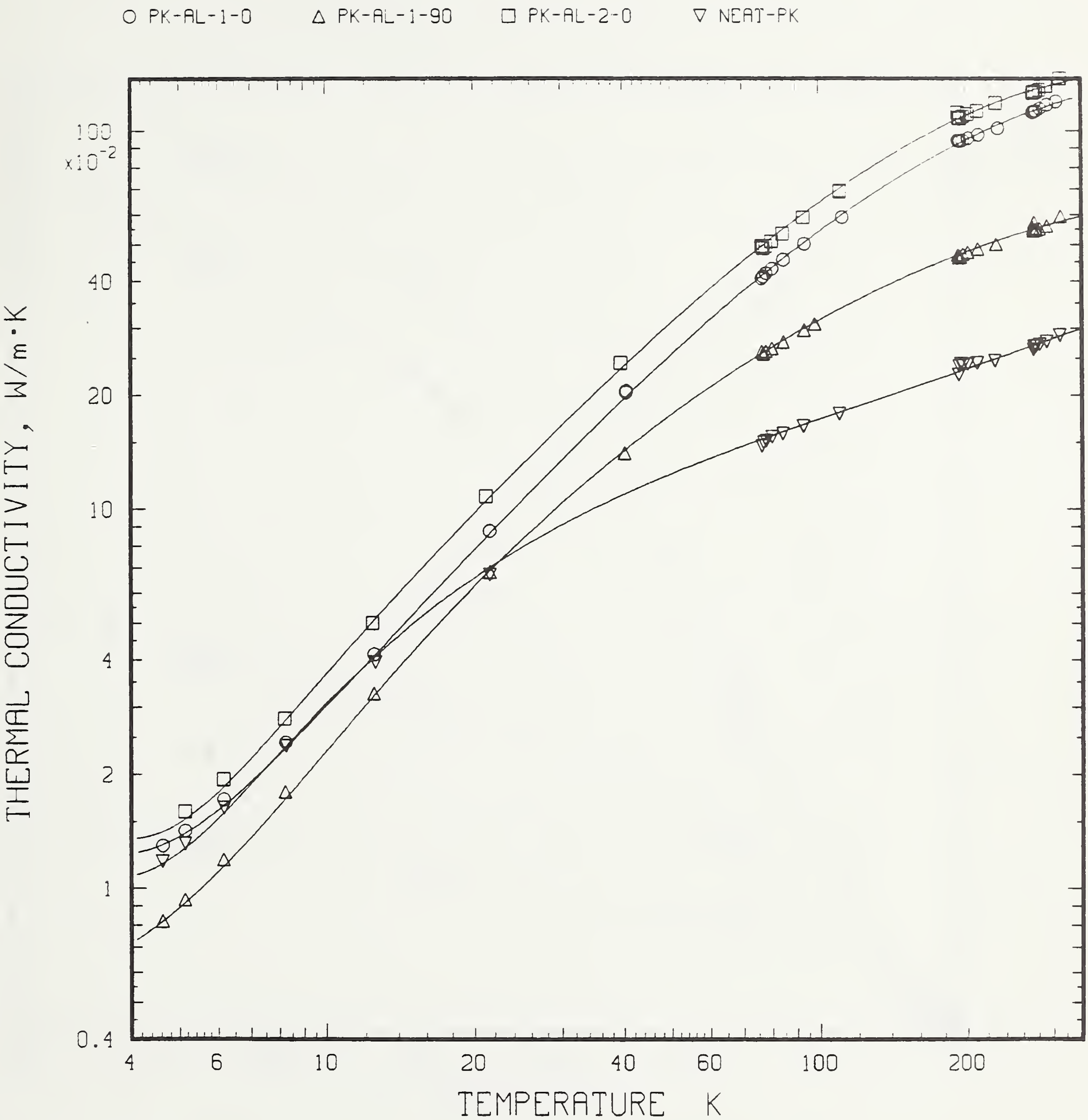



**Figure 25** Thermal conductivity of the PEEK/alumina fibered data, both parallel and perpendicular to fiber direction. The Neat-PEEK data also included. Note that both scales are logarithmic, which clarifies the behavior at low temperatures. Compare to Figure 26.

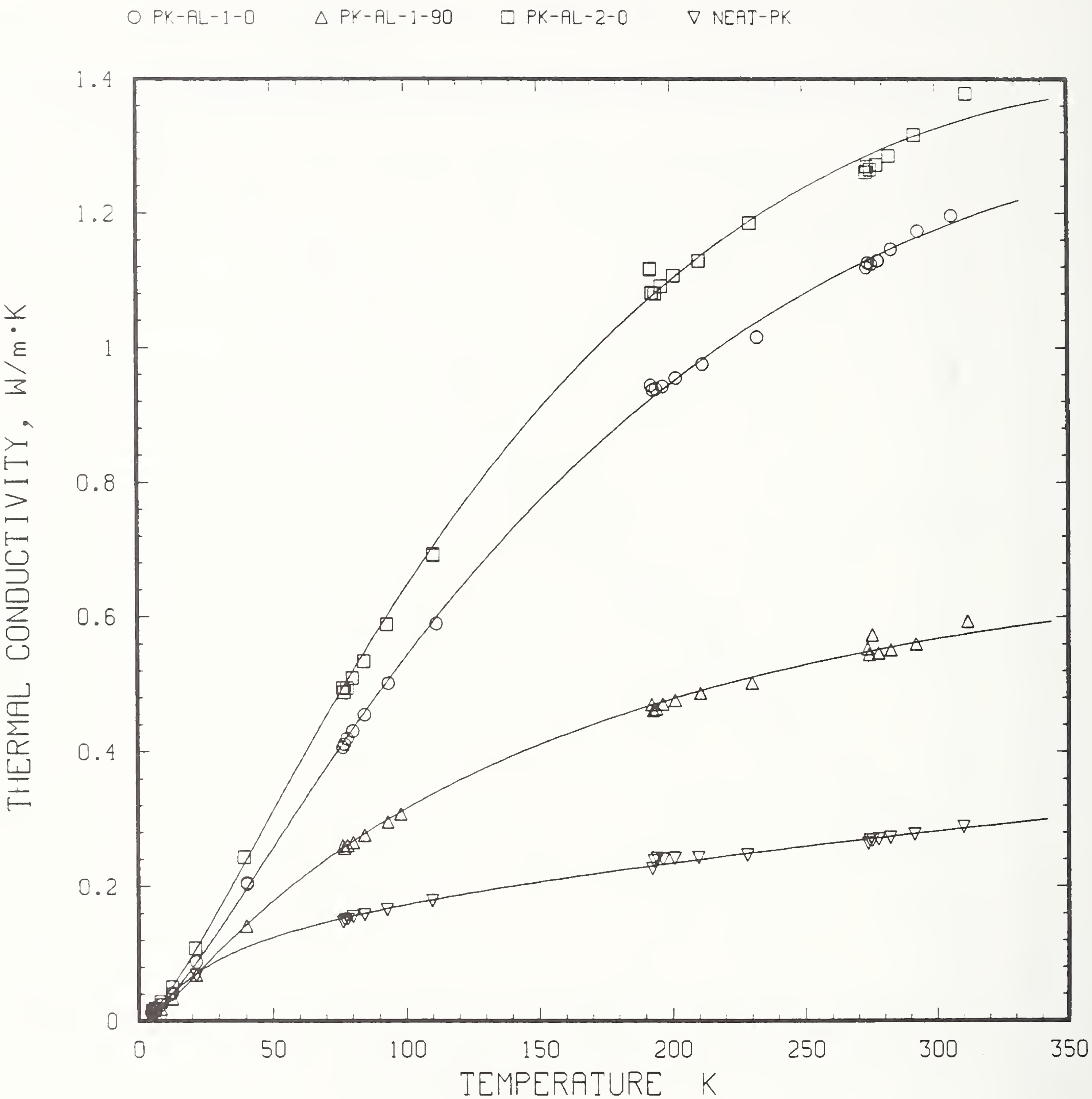



**Figure 26** Thermal conductivity of the PEEK/alumina fibered data, both parallel and perpendicular to fiber direction. The Neat-PEEK data also included. Note that both scales are linear, which clarifies the behavior at high temperatures. Compare to Figure 25.

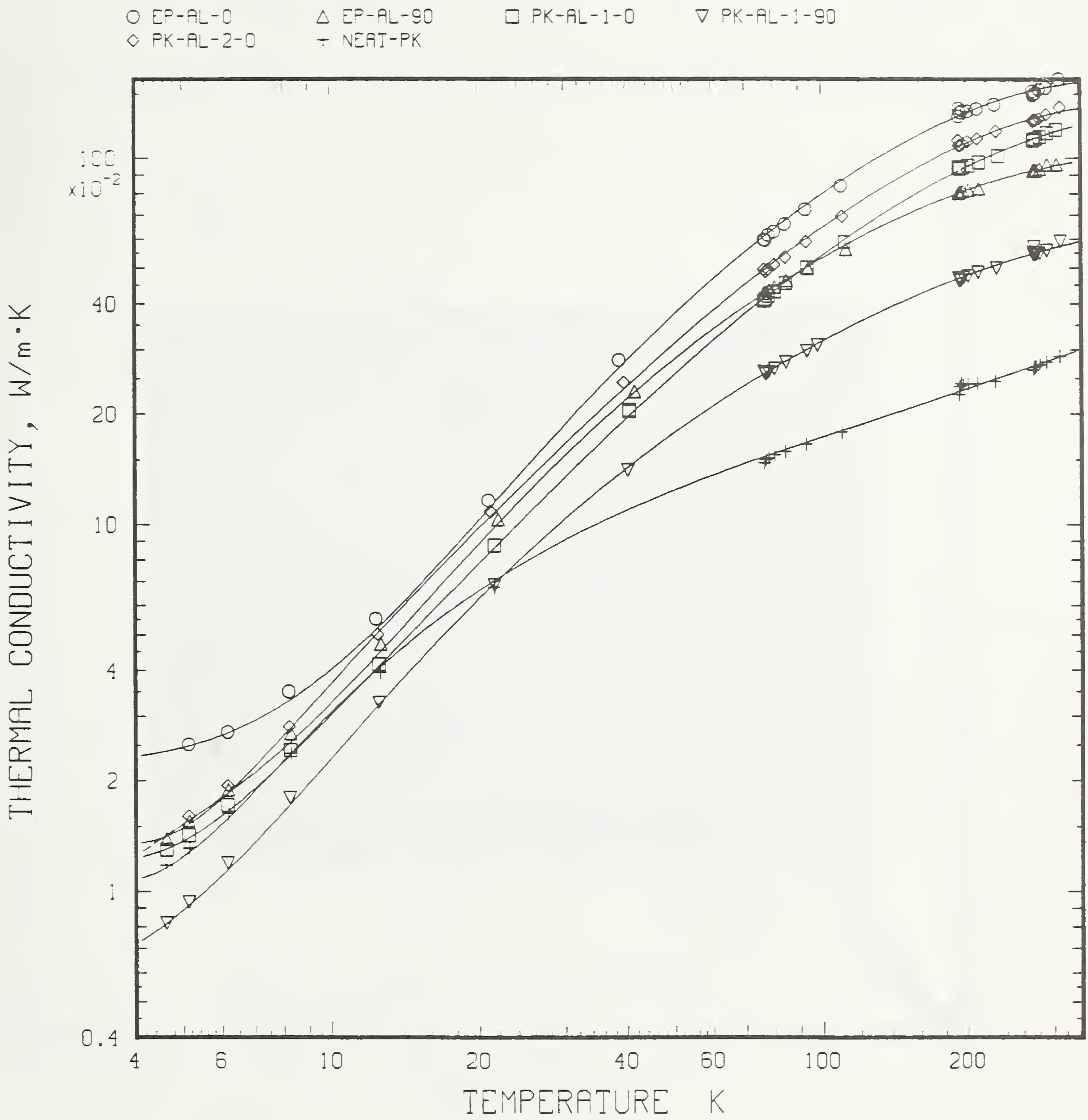



**Figure 27** Thermal conductivity of all the specimens tested. Note that both scales are logarithmic, which clarifies the behavior at low temperatures. Compare to Figure 28.

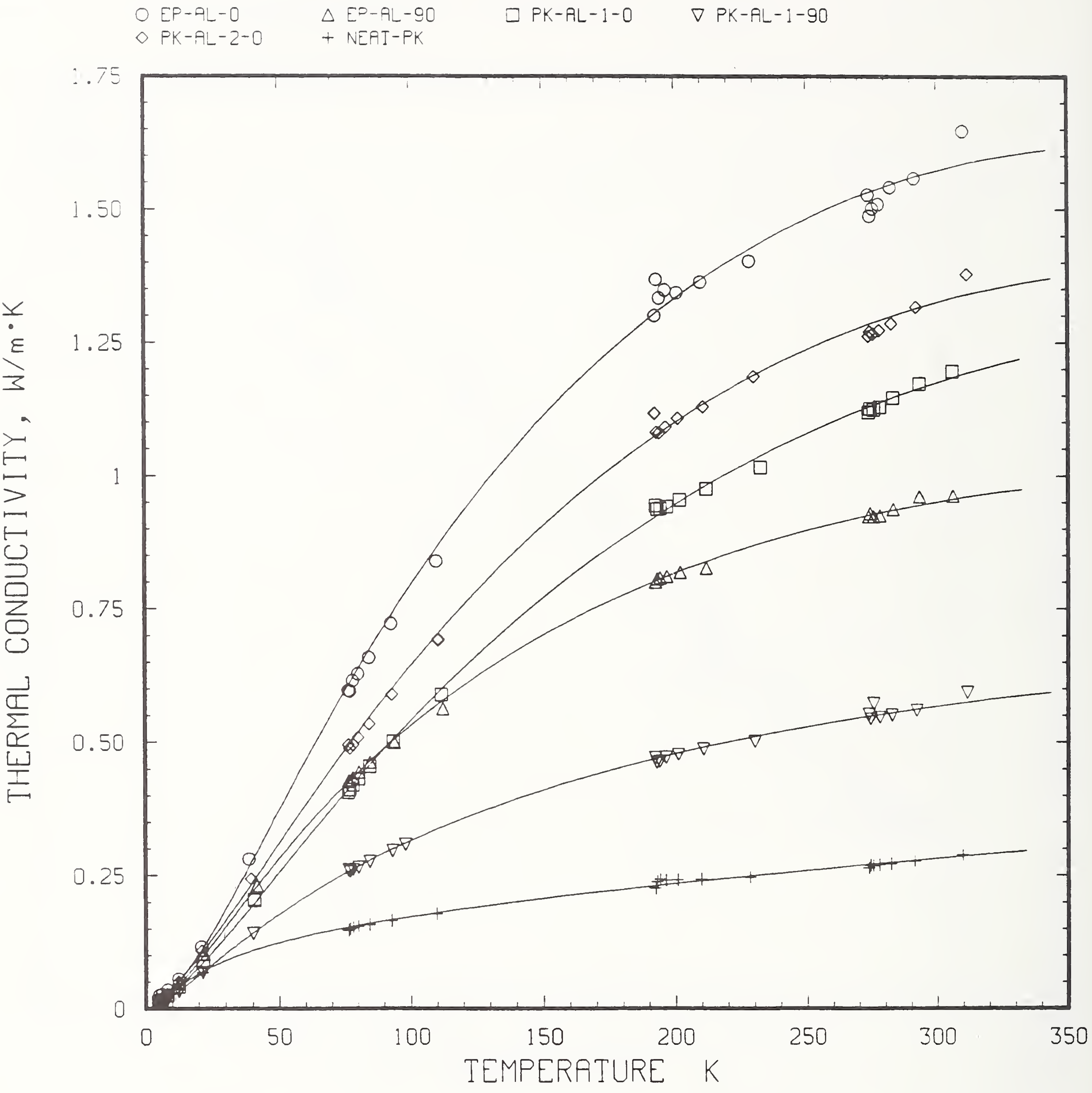
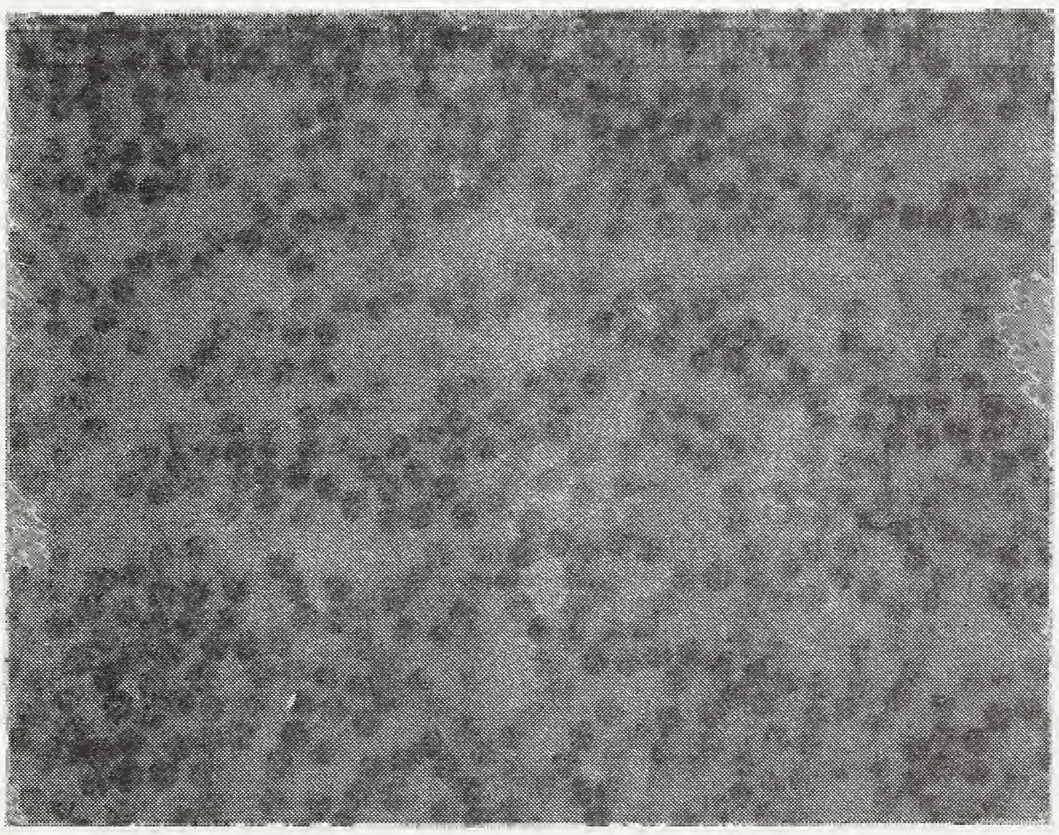
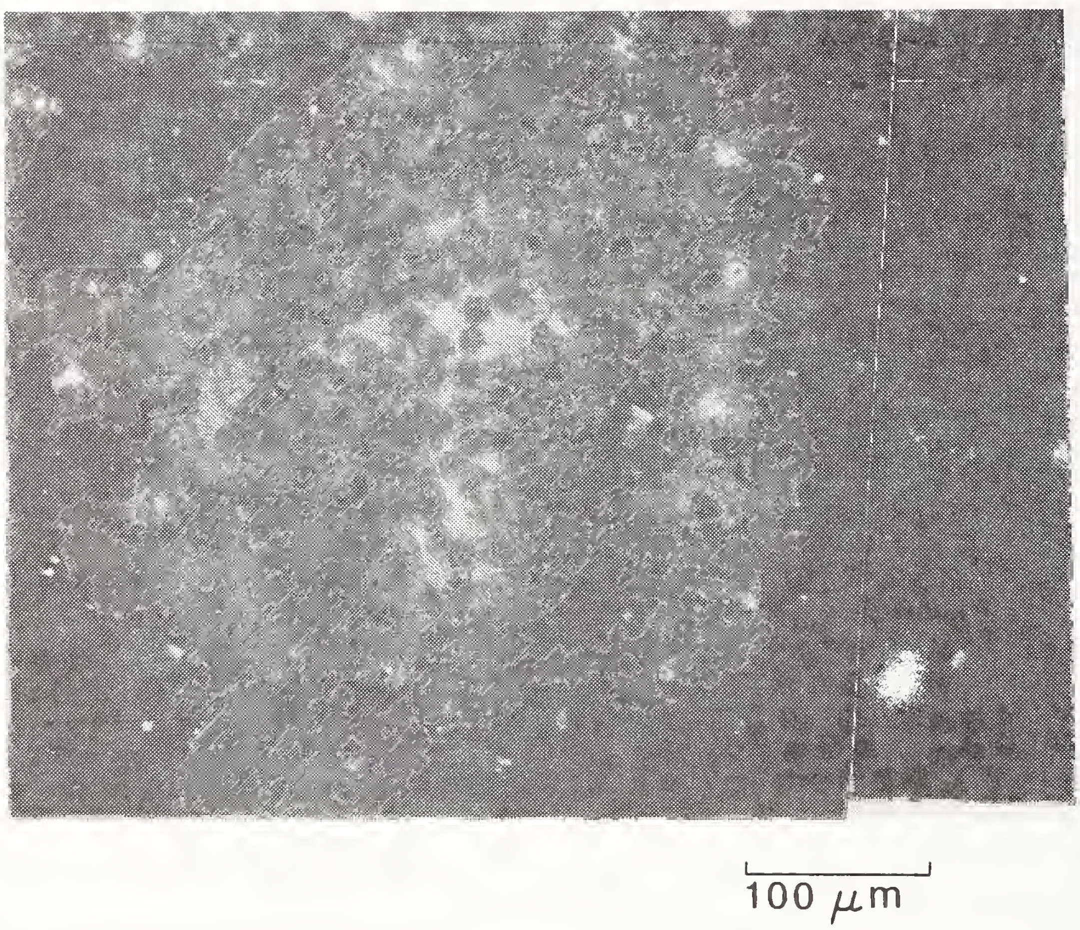



**Figure 28** Thermal conductivity of all the specimens tested. Note that both scales are linear, which clarifies the behavior at high temperatures. Compare to Figure 27.



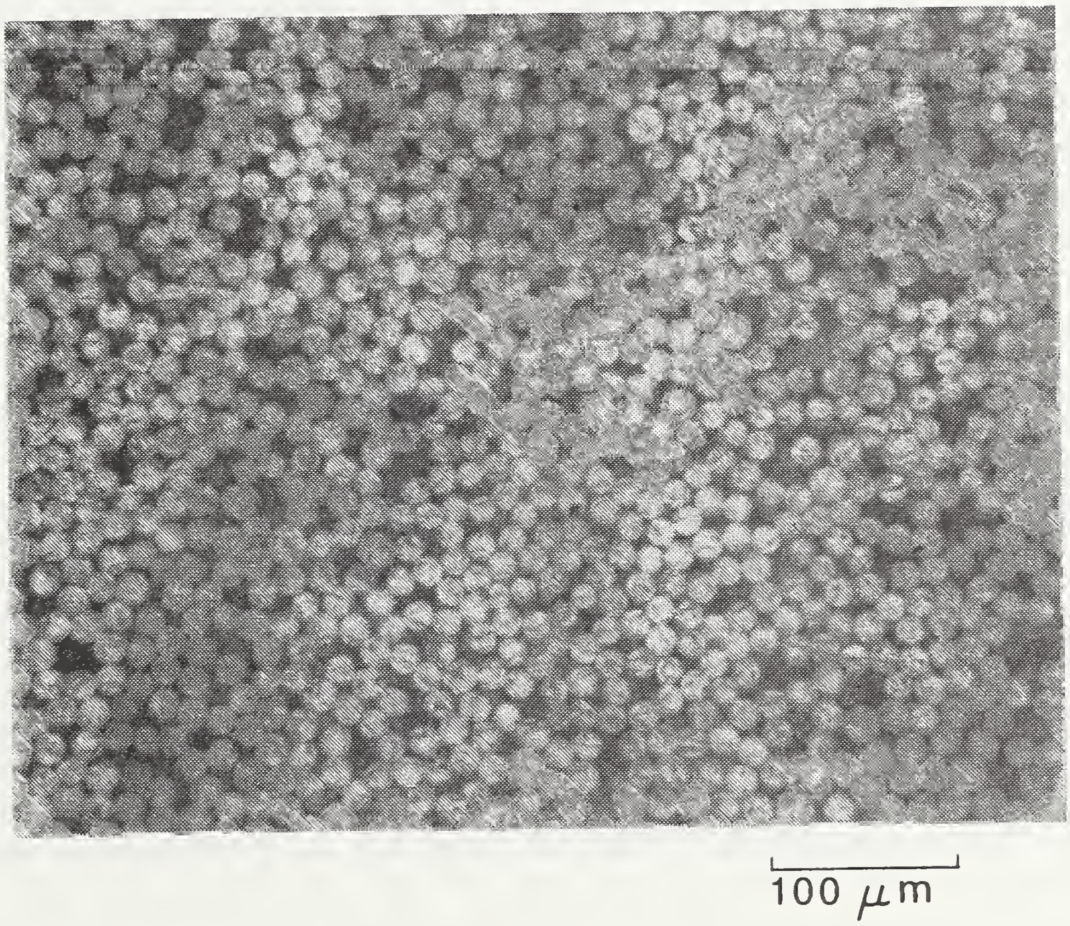
100 $\mu$m

PK-Al-1-0° photomicrograph. A larger section was used to determine the fiber volume ratio of 43%.





PK-Al-2-0° photomicrograph. A larger section was used to determine the fiber volume ratio of 52%.




EP-A1-0° photomicrograph. A larger section was used to determine the fiber volume ratio of 59%.

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D.L. Rule and L.L. Sparks

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The thermal conductivities of poly-ether-ether-ketone (PEEK), of alumina fiber in a matrix of PEEK, and of alumina fiber in a matrix of epoxy, were determined along with the effects of fiber orientation and thermal cycling. Thermal conductivity was measured over the temperature range of 4.2 to 310 K using a steady-state apparatus.

These data are presented and discussed relative to specimen characteristics. It appears that after accounting for different fiber fractions in the specimens, the thermal conductivity of the PEEK composite material is less than that of the epoxy composite material in particular temperature ranges.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

alumina; composite; epoxy; low temperature; PEEK; poly-ether-ether-ketone; thermal conductivity

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